NISTIR 6816

Manufacturing Technology:

The Road Ahead

J. C. Boudreaux

U.S. DEPARTMENT OF COMMERCE
Technology Administration
Advanced Technology Program
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Manufacturing Technology: The Road Ahead
(Extended Abstract)

J.C. Boudreaux
NIST/Advanced Technology Program

1. About the Advanced Technology Program

The *Advanced Technology Program* (ATP) provides competitive, cost-shared awards for industry to develop high-risk, enabling technologies with broad-based economic benefit. ATP seeks to help industry fill the gap between basic research and product development, and to invest in technologies that would either not be developed at all or not be developed in a competitive time frame without government cost-sharing. ATP invests directly in the nation's economic growth by working with industry to develop innovative technologies with strong commercial potential -- technologies which, if successful, would enable novel or greatly improved products and services for the world market.

ATP works as a partner with industry. While government provides the catalyst, industry conceives, partially funds, and executes ATP projects. ATP hosts public workshops to discuss and further refine the potential for high-risk but high-payoff technical innovations. Other mechanisms for getting industries' input include: advice from senior industry technical and business managers; and input from industry associations, trade groups, and professional societies.

2. Background

The ATP regional workshop *Manufacturing Technology: The Road Ahead* was hosted by USCAR in Southfield MI on June 20-21, 2000 . Participants included representatives from companies or groups of companies, technical and trade associations, academic institutions, non-profit research institutions, and government laboratories. The workshop focused on discret-part manufacturing in the belief that technological improvements in the automotive sector would have broad impact on durable goods manufacturing in such sectors as aerospace, fabricated metal products, electrical and non-electrical machinery, and precision instruments industries. [1]

The USCAR workshop elaborated upon an ambitious set of goals which had emerged as a result of consensus-building discussions sponsored by ERIM and the Auto Body Consortium with the active support and encouragement of senior U.S. automotive executives and industry experts. The highest priority was assigned to the *12 Month Car Initiative*, which was defined as a **five-year effort to reduce the time from styling freeze to start of production to 12 months.**

3. Workshop Overview

The workshop consisted of technical presentations, including presentations from ATP projects awarded in the *Motor Vehicle Manufacturing Technology (MVMT)* focused program /1/, and scribed discussion sessions in which the relevance of the technologies was examined with respect to the *12 Month Car Initiative.* The following papers in this report are extended abstracts of the technical presentations. The next section of this paper is a summary of the discussion sessions. The rest of this section consists of a brief account of three background topics which informed much of the discussion.

(3.1) Value Networks. Mature, well-established markets such as that for motor vehicles are defined in part by customer expectations. Customers expect certain levels of performance. They are prepared to be delighted by higher-than-expected levels of performance, but they are also prepared to punish products which are even slightly below expectations. Customers and the firms that serve them form what Christensen calls a *value network:*

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[1] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

"the context within which a firm identifies and responds to customers' needs, solves problems, procures input, reacts to competitors, and strives for profits." /2/ In effect, a firm and its customers are engaged in a dazzlingly complicated game during which the customers' value preferences can often evolve unpredictably. The firms' task is to build a theory of the consumer which makes sense of these varying market signals. Such theories propose to explain customer choice in terms of observable characteristics of products, that is, *attributes,* which the firm believes are critical in the "buy" decision. But many different theories are consistent with the hard data available. Even more disquieting, the attributes not only change over time but they also change *reflexively* in terms of context-sensitive responses to the prior actions of the firms themselves. Christensen describes this as follows: "once the performance level demanded of a particular attribute has been achieved, customers indicate their satiation by being less willing to pay a premium price for continued improvements in the attribute." /2/ Customer satiation is only intensified by the tendency of firms to watch the competitive situation very carefully and to rapidly converge with respect to those attributes which seem to be more highly valued. To continue participating in the market, firms need to make another play, and, to the extent possible, this play must be informed by the information gained, both positive and negative, from the outcomes of earlier plays. The target as always is to shift the product mix in a direction which the theory indicates as the most likely winning direction, showing how to move the firm's products "up" the customers' value chain.

(3.2) A Systems View. From the producer's point of view, engineered products, from consumer products to the industrial plants used to fabricate them, are *systems.* Systems are assumed to be separated from the rest of the universe by means of a physical or conceptual boundary, and everything outside the boundary is part of the system's environment. Systems are composed of interacting parts, each of which is separated by a boundary and interconnected by (I/O) links such that the outputs of one component are linked as inputs of others, and conversely. Systems, and system components, are stratified in the sense that single components at one level may be further resolved into networks of components at the next lower level. Since the overt behavior of a system is defined in terms of behaviors of its components and the rules which govern their interconnection, one winning play is to discover and productize an innovative improvement in a bounded set of components which then boosts hitherto unexploited, or underexploited, attributes to otherwise unreachable performance levels. If appropriate intellectual property protections are put in place, the innovation itself becomes a technological barrier against the firm's competitors.

(3.3) Platform Sharing. Automakers have adopted *platform sharing* to distribute the cost of design, engineering and manufacturing over a number of outwardly distinct models. The idea is a modern variant of economies of scale: by producing standardized modules in high volumes, it is possible to reduce tooling costs, decrease materials prices by bulk purchasing, and also increases the productivity of labor by reducing "learning curve" costs. There are differing opinions about how to define automotive platforms. For example, some have suggested that a platform is a group of components which include engines, gearboxes, axles and suspensions, and floorpans. But this approach is only one among many equally plausible alternatives. In general, platform sharing is a matter of mixing and modifying automotive technologies. That is, platforms are bundles of standardized components and technologies which are either imperceptible to the customer or only perceptible through the enhanced levels of performance of highly valued attributes. But when the effects are both highly valued and directly experienced by the customer, then the incentive is to support them as differentiating, that is, non-platform, components and technologies. The critical impact of platform sharing on the *12 Month Car Initiative* is that this strategy implies that innovation pathways for components and technologies may have (very) different time horizons, some short and some very long and that the key management decisions are whether to launch an effort on one of these pathways and how to effectively coordinate cycles with such differing time scales.

4. Discussion Summary

There was near consensus on two points. First, the central goal of the *12 Month Car Initiative* could not be achieved by pointwise improvements in engineering and manufacturing alone, but would certainly require coordinated improvements in many interdependent technologies, including concurrent developments of both manufacturing processes and new materials, e.g., design and formability issues for aluminum alloys, advanced composites, and so on. Second, to be feasible, there would have to be a deep commitment to *parametric engineering* and *science-based simulation and modeling tools*. In brief, there will be a substantial role assigned to information technology. Though the discussions were wide-ranging, four technical themes were emphasized: (1) collaborative innovation environments, (2) manufacturing processes and material systems, (3) design models and process simulations, and (4) parametric engineering.

(4.1) Collaborative Innovation Environments. An assumption is that innovation is an effort bound by

already well-defined requirements and specifications. Such an approach places a heavy burden on OEMs, who are inclined to push the costs of specification onto the suppliers, where (arguably) it belongs. Application engineers at the suppliers will have a clearer vision of the "to-be" part and are better able to harden that vision into a technically feasible and financially sound work plan. What suppliers lack is an integrated understanding of the part from the perspective of the final product, that is, an understanding of the part as a system component of the final product. The auto companies have made significant investments in web-based methods to support the business-to-business (B2B) processes. This critical step allows us to organize and communicate across the large and interlinked automotive supply chain. But it now appears to work effectively for purchasing already developed off-the-shelf parts. But it is not clear that this approach will be equally effective when innovation is required and the part is only one component in an interactive network of components. The quality of the whole depends upon a cross-supply-chain ability to develop and use specifications for shared interfaces between (often remote) components. That is, if two suppliers are making linked components, then the interfaces between all of these components must be specified in sufficient detail to allow each supplier to design test and validation procedures for its part and also to serve as a basis for integration testing even while the parts are being designed. These interfaces are multimodal in the sense that they may require geometric, mechanical, electrical, thermal, fluidic, and/or chemical specifications.

(4.2) Manufacturing Processes and Material Systems. The manufacture of durable goods is subject to the logic of material flow: a stream of components needs to be acquired, and then, after a suitable lag, a stream of assemblies of the components is released. Components flow from one workstation to another. One major concern is how much stacked-up variation will be generated in the output assemblies from the possible sources of variation in the processes themselves and their inputs. Even if we assume that the input parts are rigid bodies, small rotational errors in alignment can cause large overall dimensional errors in the finished assembly. And if this source of variation is significantly reduced, joining processes are even more significant sources of variation. For example, the heating of the material in a welded joint can cause significant deformation.

General Assembly. General assembly in automotive manufacturing includes installation of interior and exterior trim, instrument panels, seats, the powertrain assembly, steering assemblies, brakes, electrical, suspension, and, in the case of trucks, frame assemblies. The success of cost-effective and quality assembly is determined by the teams that design, build, and supply subassemblies to the general assembly area. Because component assembly is so diverse, general assembly has been left largely untouched by technological productivity improvements. Success in this area depends on solutions that impact suppliers of subassemblies and suppliers of production equipment. Critical areas for technology development and deployment in the context of the *12 month Car Initiative* include material handling to and from the assembly line extending across the supply chain; new joining technologies to reduce the number of discrete fasteners in joining dissimilar materials; and inspection technologies to validate assembly processes and ensure the integrity of components both before and after assembly.

Constructive technologies for rapid fabrication of production tooling and functional parts. In the automotive industry the longest lead time in producing a new product is the design and fabrication of production tooling, including such items as molds for plastic parts, dies for die casting, and stamping dies. The traditional approach is machining tool steel, a time-consuming process. Several methods have been developed for the rapid fabrication of prototype or limited-run tooling, but the tooling produced is typically not amenable to production molding or casting processes. In addition, the tool materials are usually unable to address demanding metal-forming processes, such as forging, stamping, or casting, because of their limited temperature capability and hardness. Emerging constructive technologies that build up the desired shape rather than cutting it out of a blank offer a potentially revolutionary approach, not only for fixtures and tooling, but also for parts with features and geometries that cannot be obtained with conventional metal removal processes. These rapid fabrication technologies permit miniaturized sensors and actuators to be embedded in both tooling and products, and thus can empower designers to create new designs not previously obtainable. The targets of opportunity in the context of the *12 Month Car Initiative* include metal spraying, investment casting using rapid prototype models as patterns, vapor plating, direct metal deposition, three-dimensional printing, droplet-based manufacturing, free-form fabrication, and free-form powder molding.

Net shape forming of advanced materials. Lighter weight advanced engineered materials, originally developed for the defense and aerospace industries, can reduce emissions and fuel consumption for the North American ground transportation fleet without significantly compromising vehicle packaging and safety. These engineered materials, primarily consisting of a matrix (polymer, metals, or ceramics) and synthetic fibers (glass, polymers, or ceramics), are now too expensive for adoption and widespread use in the automotive industry. The adoption of these materials depends on the development of manufacturing technologies which exploit their near-net-shape fabrication capabilities. Many alternative technologies for these advanced materials, such as vacuum die casting, semi-solid forging, precision forging, squeeze casting, metal injection, ceramic injection, plastic injection,

reactive molding, and powder metal processing, need to be explored. The targets of opportunity in this area include dimensional repeatability, reduction in physical variation through real-time sensing and control, interface chemistry control, and (more generally) increased process reliability.

(4.3) Design Models and Process Simulations. Direct use of product data in production, and feedback of process information to process designers, can reduce the lead time and improve the accuracy of process tooling. Several manufacturing processes are tightly coupled to the product design. Examples include stamping dies, molds, assembly fixtures, inspection gages, packaging, material handling and other interfaces. Process designs (like stamping dies) are done at organizations that are suppliers to the product manufacturer, requiring data models to flow down the supply chain. Three hurdles require expensive manual intervention. The product model may be incomplete with respect to the details needed to generate tooling, requiring additional information. There may be errors in the product model (such as sliver surfaces or line fragments) that do not show up in drawings but clog CAM software. The accuracy of process design systems may be limited and not may not compensate for actual production results, such as springback or shrinkage. Process information needs to be captured in a way that not only supports continuous improvement within a single process, but also closes the process loop with upstream and downstream processes. For example, an assembly operation should be designed on the basis of dimensional information from the process that manufactured the parts to be assembled, rather than relying only on product models of those parts that do not take account of manufacturing variability.

(4.4) Parametric Engineering. New methods for product design are also critical for the *12 Month Car Initiative*. Parametric Engineering is an advanced feature in CAD systems that permit rapid design of a family of parts, which are parametrically related. For example, there could be a parametric design for a bracket where the engineer only has to specify a few parameters (like length and attachment angle), and a complete detailed bracket design would be produced. This technology holds great promise to reduce the lead time of product and tooling design, but new solutions are needed to evaluate the manufacturability, dimensional consistency, and cost implications as derivative parts are designed. There is also a need to be able to aggregate parametric parts designs into the parametric design of assemblies, where tradeoffs between component parts are optimized. **/3/**

/1/. Boudreaux, J.C. and Lettieri, T.R. *Advanced Technology Program Motor Vehicle Manufacturing Technology Public Workshop (NISTIR 6079)*, October 1997; 435 pages.
/2/. Christensen, C.M. *The Innovator's Dilemma*, Harper Collins, 1997.
/3/. VanderBok, R., personal communication, May 15, 2001.

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Strategic Directions for the New Millenium for the Auto Industry

Ray VanderBok
ERIM

Abstract. This presentation will describe the results of a recent workshop by automotive manufacturing executives to articulate a strategic vision for the new millennium. The auto industry is now responding to new set of global challenges. The auto industry is rapidly changing; prompted by e-commerce. New information technology and supply team relationships promise to profoundly impact the way this industry does business. This presentation will propose initiatives to meet these needs.

Agile and Precision Stamping Program - Near Zero Stamping (NZS)

Ernie Vahala
Autobody Consortium

Abstract. The NZS program is funded by NIST-ATP, and involves 24 companies and 5 research institutes. The goal of the program is to significantly improve the competitiveness of domestic die and stamping manufacturers by developing advanced technologies to achieve precision and agile stamping. The R&D efforts cover all cycle of the sheet metal development process including product design, die processing, die design, die construction, die tryout, production, and subassembly. This presentation summarizes the significant research and development accomplishments that have been made in the past years. Those R&D efforts have drastically advanced the technology and lead to the successful fulfillment of proposed R&D objectives.

New Approach to Produce Hydroformed Tailored Tubes

Stefan Heinemann
Fraunhofer Center for Laser Technology

Background
Tailored tubes are very similar to tailored blanks both of them are based on joining two metals with different strength together to create local reinforcements. The benefits of tailored blanks and tailored tubes are very much the same, such as:
- decreased weight
- increased stiffness and overall performance
- increased fuel efficiency
- cost savings through part consolidation.

The market of tailored blanks has rapidly developed over the last five years and represents as of today more than $ 100 mil. Tailored tubes are still in an exploratory stage and no applications in production have been reported yet. There are several reasons for that, the most important being that hydroformed tubes were heavily pushed over the last couple years. Hydroformed tubes allow significant cost savings through part consolidation and tight geometrical tolerances. However, weight savings are limited due to the fact that tubes of only one material grade and thickness are used. Sectionized reinforcement of the tube will take hydroformed, tailored tubes to the level of deployment we nowadays see for tailored blanks.

State of the art to produce tailored tubes is to butt weld two tubes of different thickness or strength together as shown in figure 1, top. Precise edge preparation is needed to result in a weld of high integrity. The tubes will show the same OD, but might have a slightly different ID. Another way to manufacture tailored tubes is to put a sleeve around the tube and weld the edge of the sleeve to the tube or weld the sleeve to the tube by welding through the sleeve as shown in figure 2, botton.

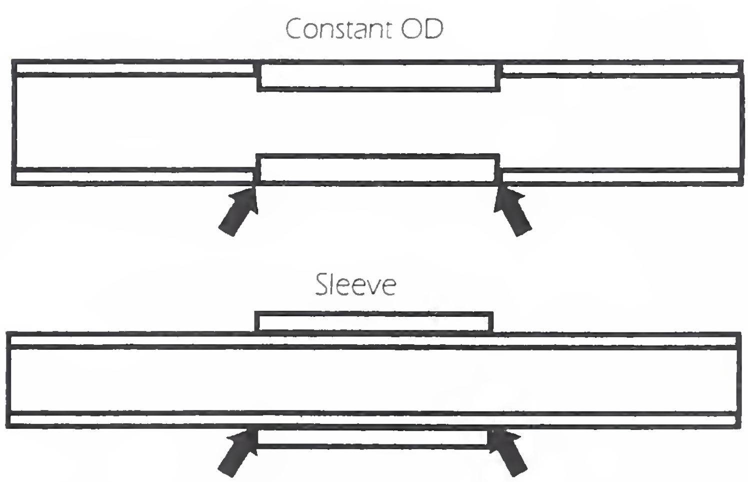

Figure 1: Conventional processes to manufacture tailored tubes. Above is shown the butt welding of two tubes with different thickness, below is shown the welding of a sleeve to a plain tube. The red arrows indicate the areas of (laser) welding.

Metal Foam

Localized reinforcement of tubular structures can also be achieved by inserting metal foam inside the tube. Metal foams are based on a unique technology that has been developed by Fraunhofer a few years ago. Metal powder is mixed with a foaming agent, titanium hydride, and pressed or extruded into flat sheet or round stock material as shown in figure 2

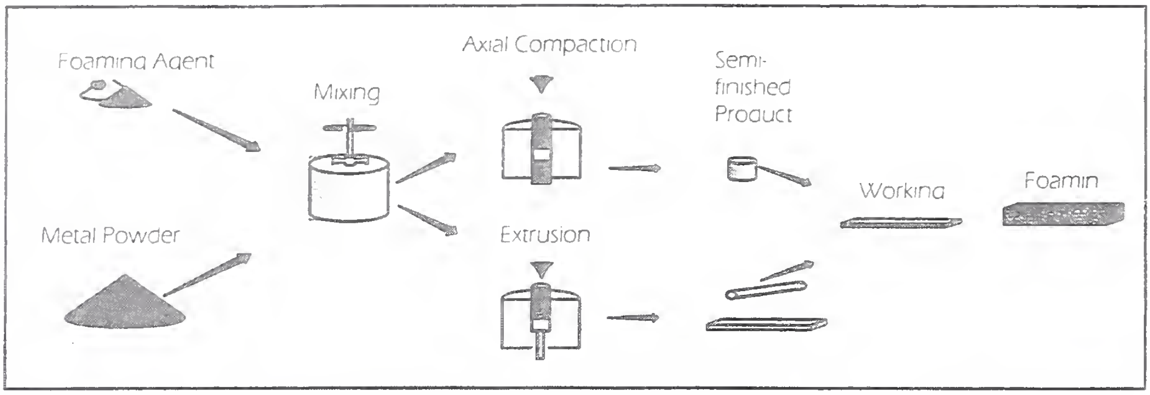

Figure 2: Metal foams are produced from metal powder and a pulverized foaming agent, such as titanium hydride, that are mixed and subsequently pressed or extruded to result in solid precursors. Source. Fraunhofer Center Delaware.

The precursors can be stamped into any shape before they are heat treated to cause the metal foam to expand by approximately a factor of four. The closed cell porosity of the foam can be adjusted in the range of 30 to 90%, allowing the mechanical properties to be tailored over a wide range. Metal foams can be made from steel or aluminum and offer high strength, high stiffness, excellent energy absorption properties and weight savings. This allows light weight structural components with excellent stiffness to strength and strength to weight ratios that in turn yields to superior crash impact behavior and high bending strength. Applications in production are the firewalls in some convertibles, but might include others, such as side rails, engine cradles or cross members. Some applications are shown in figure 3.

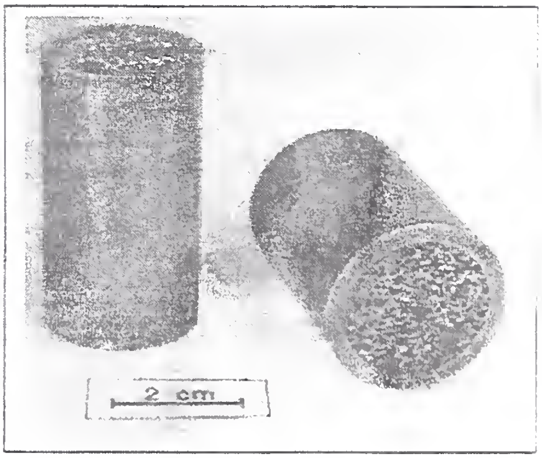

Figure 3: Metal foams precursors are typically placed between two face sheets. The parts is press-formed and subsequently foamed in the die (left picture). Aluminum foam metallurgical bonded to the ID of aluminum (6061) tubes (right picture.

Some data on mechanical characteristics are available for aluminum foams. The flexural strength has been measured as a function of porosity and it was fund to go from 7MPa at a density of 0.2 g/cm3 up to 90 MPa at 1.5 g/cm3. Compression tests revealed that the loading curve is very similar to the one of Polyethylen foam, but strength of the aluminum foam is approx. 50 times higher. The correlation of the Young modulus and the porosity is shown in figure 4.

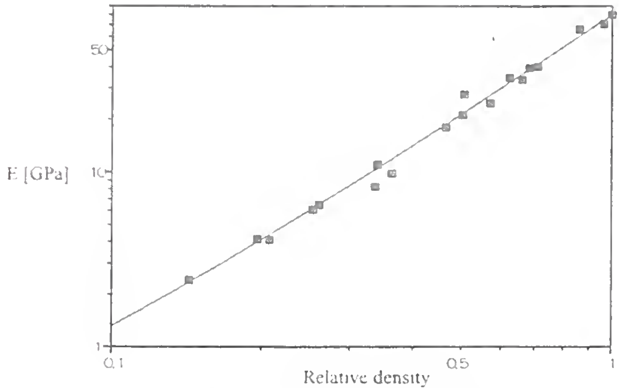

Figure 4: Correlation of Young modulus and porosity for 5xxx series aluminum foam.

Production of Tailored Tubes

Two Fraunhofer Centers, the Center for Laser Technology and the Center for Advanced Materials are combining their know-how in roll forming, laser welding and metal foam technology to develop the process for continuous production of tailored tubes. The concept involves aluminum or steel coils being fed into the roll former where several roller stands continuously form the flat strip into a round tube. The metal foam precursors are inserted on the fly into the preformed tube before the final roller stands completely close the tube. As it continues to run, a laser is used to tack the foam bits into place for positioning the precursor at the spot of the reinforcement. The special design of the weld box and beam delivery allows the welding of tubes with a thin wall, but large OD with perfect weld integrity. This is done without the aid of a seam-tracking device. A production tube mill for small sized tubes is shown in figure 5.

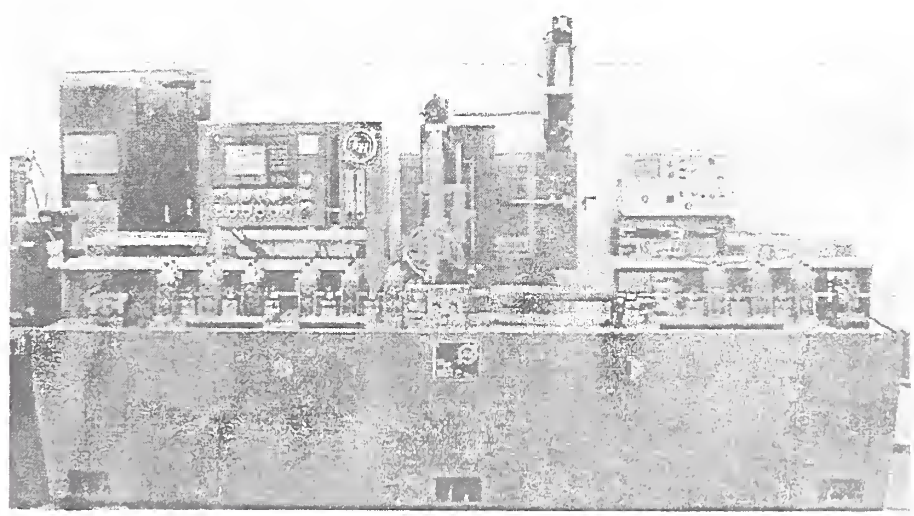

Figure 5: Tube mill for the production of small sized tubes. The red arrow indicates the area where the foam precursors are inserted prior to closing the tube.

Tubes are cut to length and ready to undergo conventional bending and hydroforming processes with no interference from the metal precursors. After hydroforming the tube needs to be tempered in a furnace at temperatures around 650 degr.C to cause the metal foam to expand and to make a metallurgical bond to the ID of the tube. The porosity, material, composition and amount of the metal foam can be varied thus all impacting the increase of strength and stiffness in the reinforced area. First experiments have been done using aluminum metal foam inside an aluminum tubing and metal tubing. The technology is not limited to round tubes, but any shape can be realized. A patent on the process is pending

Technical Challenges

Aluminum foams in both aluminum and steel tubes, as well as steel foam in steel tubes, are being investigated. Wayne State University (Detroit, MI), the academic partner of the CLT, will do forming and mechanical testing of the samples. The most important fields needing research are:

1. What are the torsional and bending strength as well as the crash worthiness and damping characteristics of the finished tube?
2. How do those parameters depend on the material and the composition of the metal foam?
3. Can the metal foam and the tubing be made from the same material and how does the tempering, needed to activate the foaming, impact the mechanical properties and part tolerances of the finished product?
4. What are the mechanical properties of steel tubes reinforced with aluminum foam and different alloys for aluminum foam?
5. How is the long term behavior, such as corrosion and fatigue?
6. How does the process compare economically to state-of-the-art technologies?

Remaining Technical Challenges in Automated Part Design, Analysis and Tooling Optimization for Stamped Sheet Metal Products

NIST Manufacturing Technology Workshop
Southfield, Michigan
June 20, 2000

Dan VandenBossche
Sr. Mgr. eConnect For Volume Production

Introduction

Several recent ATPs have dealt with automobile manufacturing. The 2mm Program addressed sheetmetal assembly tolerance reduction. The Near Zero Program addressed stamping variablity. The Intelligent Resistance Welding Project focused on spot welding of body sheetmetal. Finally, the Springback Predictability Program sought more accurate models for predicting the response of steel and aluminum sheet during forming.

Having been associated with all of these programs, it is apparent that several technical challenges remain to be addressed, especially in the areas of component and tool design methods, and process technology.

Design Methods

Design For Aluminum   Significant challenges face the expanded use of aluminum in the automobile. First is cost. With its density and Young's Modulus 1/3 that of steel, and cost of about four times that of steel, the cost penalty for an aluminum part with the same stiffness is about twice that of steel. Second is formability. Part design today is critical with aluminum and has only been applied to easily formed panels (Fig. 1). To achieve the kinds of shapes commonly produced in steel will require research into new alloys, lubricants, and drawing methods. Finally, assembly using current spot welding practice is not robust and the use of fasteners is expensive. Other joining methods like laser welding (Fig. 2) need to be explored and possibly adapted to high volume production.

Figure 1 - Design for Aluminum

Figure 2 - Laser Welding

Capture and Use of Best Practices Never in the history of mass production have we gathered more data off the plant floor than we do today. We have to do a better job transforming it into useful information and knowledge about how our processes perform and how product design can enable higher quality and lower cost manufacturing. Most "books of knowledge" today are little more than electronic file cabinets. Knowledge management tools could help in sorting through this data and provide useful information in a form and at a time that make it most useful. At the same time we must make it a learning tool that fosters continuous improvement.

Feature-based and Generative Design Tools The incorporation of features into our CAD systems will not only simplify the design task but will provide a means to apply manufacturing constraints to the design as it evolves. This may be the best way to apply best practice to design and to the manufacturing process. The most progress has been made in the machining area with many features identified along with the process information for manufacturing them. like holes. slots, surfaces, shafts, etc. More work is required in defining features for stampings (Fig. 3). The next step will be the combination of features as objects with generative design tools that will essentially eliminate 80% of the mundane design work for components and tooling with features defining the functional areas and generative tools providing the design logic. Challenges in this arena include getting the CAD vendors to provide the required level of extensibility and functionality so that users can define features in their own domains and easily define the rules for geometry creation.

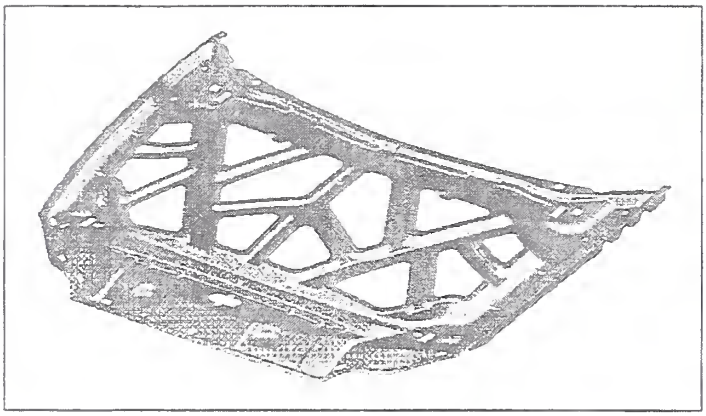

Figure 3 - Stampings consist of numerous features.

Collaborative Design The new "e-tools" hold the promise of shortening new product development cycles through the use of collaborative design tools and things like portals for easy, simplified access to specific customer or industrial sector information. We need to learn how to use this new technology. There are quite a few technology providers in this space but they lack the industrial expertise to apply it successfully the first time. The users have to understand the full range of capabilities in this area and then team with the best of the providers. Their goal must be to design and implement complete systems to address data exchange, change management, flexibility in workflow definition all within the context of the business processes which we are trying to improve.

Sheet Metal Tolerancing Based on our experiences with dimensional variation in the stamped sheet metal part domain, we have been continually challenged by difficulties in reliably measuring stamped parts, particularly large. flexible panels which derive much of their dimensional integrity through subsequent assembly operations. What is the best way to hold the

panel? What about "functional build"? We might question whether ANSI Y14.5 is adequate or even appropriate for automotive sheet metal. With as much work as has been done in this area, we are still lacking a science of sheetmetal tolerancing and inspection.

Simulation One final challenge in the area of design methods is to complete our understanding of the sheet metal forming process so that we can develop better forming simulation tools. We still need a better understanding of the role friction plays in the forming process and the effects that it has on the materials and their properties. Having taken some small steps in developing more accurate constitutive equations, we need to expand our materials database. We need more robust and efficient computer codes and the processes for using them which will more reliably predict how well a design will perform in the press.

Process Tooling

New Forming and Cutting Technologies A significant set of challenges need to be addressed in the areas of process equipment and tooling technology. One of these is to improve the scalability of processes that have traditionally been limited to either low or high volume production applications. Stamping dies generally require high investment and are suited for high volume applications. But the presses they run in are highly flexible and could make one part or millions of the same part. Dedicated machining lines require large investments but the cutting tools - the drills and inserts - are highly standardized and modular, are easily reconfigured and are cheap. How can we apply the economies of scale to low volume production so that we can achieve true mass customization? At the same time, we need to continue examining how new process technologies, such as the hydroforming of sheet and tube products, high strain rate forming using magnetic pulse or electrical discharge techniques, and laser joining and cutting, can add to our flexibility and improve production scalability.

Inspection Methods and Tools The use of programmable coordinate measurement machines, which flexibly locate a wide variety of parts and measure under program control (Fig. 4), has not been as great as one might expect. Their advantages include reduced fixturing costs, they are easy to modify, and are truly scalable. There have been problems with reliability and accuracy, but the real issues behind their lack of acceptance need to be uncovered and addressed. Some of these may include their complexity and the range of skills required to operate them effectively. Other technologies also have promise for high volume production inspection. Photogrammetric tools and the use of Moire fringe techniques could have useful application. They need to be adapted to the plant floor and made easy to use.

Figure 4 - Programmable Coordinate Measurement Machine

Compensation Strategies to Reduce the Effects of Springback One final challenge in the area of process technology is how to deal with sheet metal springback. The recent Springback Predictability ATP did a lot of good work in quantifying the physical phenomena associated with springback. But the project also reinforced long held opinion that this is not a problem simply solved with better computer codes. There is a large body of experiential knowledge that could be combined with the analytical approach which in the long run yield much better and more accurate results. The challenge here is how to capture that empirical knowledge and then configure our analytical tools to leverage it. The simplest approach might be to use classes of problems, parts, or features to generalize an analytical approach rather than dealing with every simulation as a unique situation.

Closing

We have taken a look at many of the process and design challenges facing the sheet metal industry. While this presentation was not meant to be all-inclusive, it represents many of the issues that have arisen during the course of several sheet metal related ATPs. Some will be amenable to continued analytical investigation, but in many cases, given the complexity of the stamping process, solutions will rely both on science and the identification of best practice. There is certainly a tremendous opportunity for practitioners in this field to pool their knowledge and leverage the ATP process.

Magnesium Application Challenges for the Auto Industry in North America

Gerald Cole
Ford Research Laboratory

Abstract. In 1993, the average NA vehicle contained approximately 3 1/4 lbs of cast magnesium components. 2000 MY vehicles contain almost 8 lbs per vehicle; this is a compund growth rate of nearly 18% per year. If this growth rate could continue for the next 20 years, there could be more magnesium castings than aluminum; i.e. over 200 lbs. But there are significant technical hurdles to overcome in order to place magnesium in the forefront of the lightmetals industry. This presentation will discuss many of the issues which require resolution before magnesium technology can be considered a mature commercial, customer-friendly industrial supplier of cast components. The concerns are divided into product and proecess related areas: including how to describe to engineers a mechanical property database which is affected by the manufacturing process and how molten metal flows through the die, design solutions to eliminate galvanic corrosion; coatings; fastening solutions; non-destructive evaluation methodology; and new high temperature alloys for powertrain applications. On the manufacturing side, the issues considered will include: eliminating SF6 (a GW gas), rapid prototyping, new processes for high quality, reducing scrap, recycling, machining and joining,

Metal Forming: Physical Modeling and Standard Test Methods

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Issues in metal forming have been a basis of high risk in several successful ATP proposals[1]. Large strain plasticity, particularly multiaxial strain involving unloading and reloading along a different strain path (such as occurs during stretch-bending of a sheet), has proven to be extremely difficult to quantify and nearly impossible to predict. Part of the problem lies at a very fundamental level: the dislocation patterns that form and evolve in response to the deformation. Conventional plasticity theory is limited because it does not address the physical basis for a material's behavior. The internal structure responsible for all subsequent plastic deformation behavior can only be understood by considering the crystalline nature of the environment in which dislocations move and interact. For the last few years, NIST has been carrying out research to observe, measure, and predict the dislocation patterns and their effect on subsequent deformation using advanced microstructual characterization and modeling techniques. We are now working on ways to include this understanding into an improved plasticity theory for prediction of metal forming. At a coarser microstructural level, deformation-induced surface roughening plays an important role in determining the primary interaction between die and workpiece: friction. Currently, uniform friction is assumed in models of sheet metal forming. However, it is clear that significant improvements in prediction would result if the deformation-induced surface roughening, and hence local friction coefficient, could be modelled. Experiments are underway at NIST to quantify the effect of composition and microstructure on the surface roughening caused by a variety of multiaxial strain states. A generic model for deformation-induced roughening is the goal. Lastly, prediction of behavior can only be evaluated against actual measurements. To this end, NIST is investigating various methods of obtaining uniform, multiaxial strain states and measuring the forces required to generate them. Ultimately, these methods will be standardized so that these tests can be used with confidence to obtain input data for various modelling programs. This paper will discuss each of the above topics with examples and provide the current status of NIST research on metal deformation.

DISLOCATION STUDIES

The structure of plastically deformed metals has long been known to consist of intense tangles of dislocations that arrange themselves to form the walls of relatively dislocation-free cells a few micrometers in diameter[2]. Such a microstructure is shown in Figure 1. While these dislocation patterns could be seen by transmission electron microscopy, the foils required for electron transparency were so thin that the results of *in situ* straining experiments were not clearly related to bulk mechanical behavior. The research at NIST has developed a set of observational and measurement tools, based on synchrotron radiation, that are capable of following dislocation behavior in samples 0.1 mm to 1 mm thick, i.e. representative of bulk behavior[3]. A testing stage has been built on a goniometer expressly for performing *in situ* straining experiments[4]. The techniques used are diffraction line profiling, diffraction imaging, ultra-small-angle X-ray scattering (USAXS), and USAXS imaging. Of these, the most recently perfected are USAXS and USAXS imaging[5]. The scattering curve from a deformed sample is shown in Figure 2. From this one experiment, it is possible to discern whether the cell walls are sharp or diffuse and to measure the spacing of dislocations in the wall structure. While the imaging has not yet been used to determine the spacial arrangement of the dislocation structures, it has been tested on copper polycrystals that were strained to introduce a low concentration of voids on the grain boundary surfaces. Images of these voids are shown in Figure 3. This new imaging technique is expected to have extended applications.

The observations and measurements obtained by the methods above are used in a model of plastic deformation that was derived at NIST using percolation theory[6]. Such a statistical physics approach is based on the fact that there are

up to 10^{12} dislocations per square centimeter which interact in a complicated, non-linear, long-range way resulting in the universal behavior observed in experiments. This percolation theory predicts the transport of strain through the dislocation structures observed using internal variables that can be measured or evaluated by computer simulation. The result is that a deforming metal is a self-organizing critical system described by the probability that a cell wall acts as a source of dislocations (P1) and the probability that a cell wall unzips (P2K), letting through a large number of dislocations. It has now been shown that the strain hardening rate of the stress-strain curve is given by

$$dt/ds = dt/d(P2K) * d(P1)/ds * d(P2K)/d(P1)$$

where t is the shear stress and s is the shear strain.

The fundamental origins of plastic deformation are complicated and cover a large range of size scales. It is not possible for NIST to address all aspects of the problem. However, NIST has tried to organize the scientific community to focus on the issues. To that end, an international conference on dislocations was held at NIST in June 2000. Many papers presented at that conference will be published soon[7]. There was a large international attendance from countries that have made considerable headway on many of the problems that need to be solved to provide industry with the tools to accelerate die design and reduce die tryouts.

DEFORMATION-INDUCED SURFACE ROUGHENING

Industrially, this effect is usually ignored unless it detracts from the appearance of the final product. That is because deformation-induced surface roughening depends on strain, strain-rate, temperature, composition, and microstructure in such a complex way that it can only be treated on a case by case basis. However, its role in determining the friction between die and workpiece requires that accurate prediction of forming will require a more general understanding of roughening. Research at NIST has measured the dependence of roughening on the above variables under controlled conditions and used the results to model the phenomenon. The occurrence of roughening as a function of composition and microstructure (as modified by heat treatment) has been investigated in detail. Research has led to a proposed model based on moving average statistics and work is underway to evaluate this model.

A STANDARD MULTIAXIAL STRAINING METHOD

A sheet metal formability test facility (Figure 4) has been installed at NIST. Currently, the unit consists of a hold-down ring with drawbead and a set of Marciniak test[8] tools. A surface displacement analysis system has been added to measure the full-field, biaxial strain during testing. Modification of the test samples has permitted this one type of test to investigate a range of strain states from equibiaxial to drawing (Figure 5). This facility will be used to provide biaxially strained samples for the two areas of investigation above, as well as form the basis for a standard test method for sheet metal, providing basic data for finite element analyses, forming analyses, and formability measurement.

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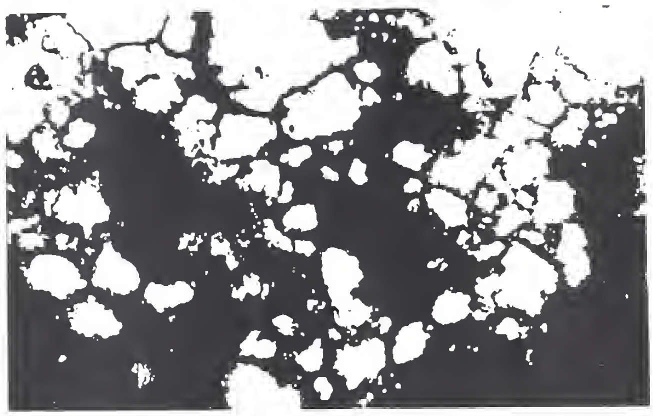

Figure 1. Dislocations forming cells in deformed copper.

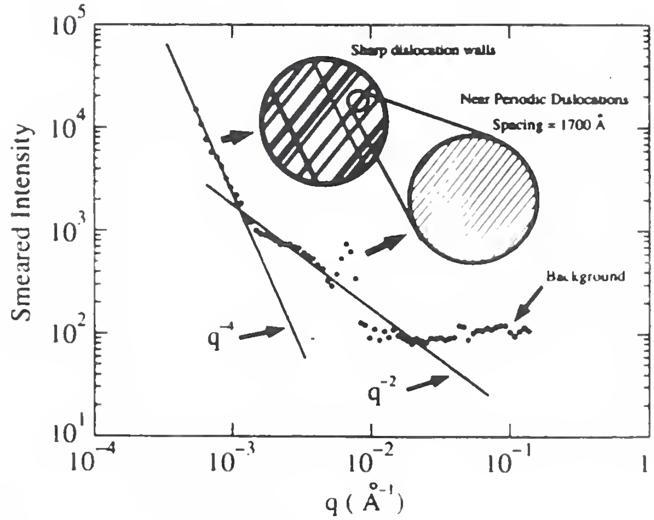

Figure 2. Scattering of X-rays by dislocation structures in deformed aluminum.

Figure 3. USAXS image of internal cavities on grain boundaries in deformed copper.

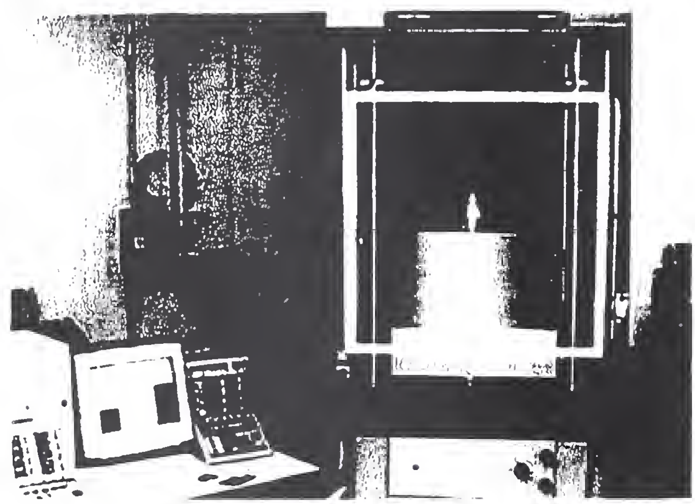

Figure 4. Metal formability tester installed in Metallurgy Division at NIST.

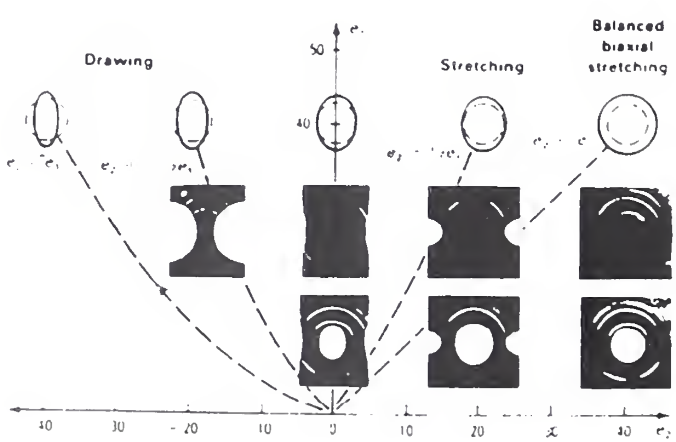

Figure 5. Strain states achievable with formability tester.

Ultrasensitive MEMS magnetometer for future thin-film technologies

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Nanometer-scale magnetic multilayer films, patterned recording media, and magnetic devices have proven to be a challenge for conventional magnetometers. Limitations on sensitivity stem from low sample/sensor volume ratios typical of conventional magnetometers. Sensitivity can be improved tremendously by integrating samples with the measurement transducer using microfabrication methods. In particular, we are developing a new class of magnetometers based on microelectromechanical systems (MEMS) for measuring magnetic forces and torques on samples deposited onto microscopic flexible structures. As an example, consider the simple MEMS sensor having a thin magnetic film deposited onto a micromachined torsional oscillator. When the oscillator is excited resonantly by an external ac magnetic field its peak angular displacement is proportional to the magnetic moment of the film. We refer to this device as a micro resonating torque magnetometer or μRTM. In principle, a torque as small as 10^{-20} N-m can be detected at room temperature by measuring the resonant frequency shift of the oscillator, whereas the best torque sensitivity for conventional instruments is 10^{-10} N-m. We estimate that the μRTM will have sensitivities similar to those measured in an integrated-sample dc SQUID experiment, approaching the quantum limit (100 μ_B at 4.2 K). The μRTM will be far superior in higher magnetic fields and at higher temperatures where the sensitivity of SQUID sensors degrades rapidly. The main noise source for the μRTM is the thermal excitation or Brownian motion of the mechanical resonator. For sufficiently high mechanical Q, low moment of inertia, and low spring constant, the thermal noise issue can be minimized. We are starting a program for fabricating and testing μRTMs along with other novel MEMS magnetometers in the micromachining facility at NIST in Boulder. The goal is to optimize signal-to-noise ratios with devices that are within the design rules afforded by standard surface and bulk micromachining techniques. MEMS magnetometers like the μRTM will allow us to perform accurate measurements of thin-film samples and active devices with nanometer dimensions under ambient conditions. We present some results obtained in our laboratory using commercially available silicon micro cantilevers. These results illustrate the potential for MEMS magnetometers. In particular, we discuss M-H loops measured with a μRTM and micromechanical detection of ferromagnetic resonance (FMR) based on calorimetry, magnetic-moment torque fluctuations, and direct angular momentum absorption of circularly polarized microwave photons. One immediate application being considered is to use MEMS magnetometer chips as disposable substrates for measuring the magnetic properties of ultra thin films under deposition, processing , or corrosion conditions.

The magnetization M in a magnetic film will generate a mechanical torque T in the presence of an applied torque field H_T (see Fig. 1). In many cases, thin-film shape anisotropy is sufficient to generate mechanical torques that can be measured with micromachined detectors. In particular, measuring T allows the determination of the saturation magnetization M_s when a sufficiently large field H_o is applied in the plane of the film: $T = \mu_o\,|\boldsymbol{M}_s \times \boldsymbol{H}_T|\,V = \mu_o M_s H_T V$, where V is the volume of the film (given that the angle between the plane of the film and $\boldsymbol{H}_T$ is set to 90°).[1] For a 10 nm thick Fe film 50 μm wide by 450 μm long ($m = 2.4 \times 10^{-10}$ A m^2) with $H_T = 90$ A/m we calculate $T = 2.7 \times 10^{-14}$ N·m.

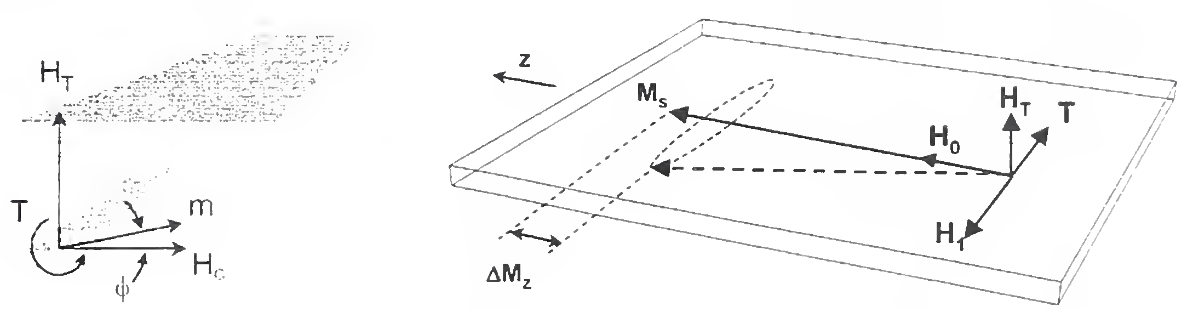

Fig. 1. Vector diagrams showing the orientation of the applied fields and mechanical torque generated in an FMR experiment.

If the magnetic film is deposited onto a microcantilever, then in principle, we can compute the torque knowing the geometric parameters of the cantilever. For small twist angles φ, $T = k\varphi$, where k is the torsional spring constant. According to elastic theory, [2,3]

$$k = \frac{wt^3 E}{6l(1+n)}, \tag{1}$$

where E is the Young's Modulus, n is the Poisson ratio, t is the thickness, w is the width, and l is the length of the cantilever.

The change in the mechanical torque under FMR conditions for a thin film is given by

$$\Delta T_{FMR} = \mu_0 \Delta M_z H_T V, \tag{2}$$

where ΔM_z is the change in the magnetization due to the FMR precession of M (see Fig. 1). For a microwave field $H_1 << M_s$ [4,5]

$$\Delta M_z = \frac{|m_{in}^2|}{2M_s} \approx \frac{(H_1\chi'')^2}{4M_s}, \tag{3}$$

given that $|m_{in}| \approx H_1\chi''$ for small FMR tilt angles. Here m_{in} and χ'' are the in-plane magnetization and the imaginay part of the susceptibility at resonance, respectively.

A bimaterial calorimeter for FMR can be understood within the mathematical framework developed for other bimaterial thermal sensors. Consider the silicon cantilever with its metallic coating as a rectangular beam fixed at one end comprised of two layers that have different thermal properties. Barnes *et al.*[6] solve the heat equation for this configuration and show that the deflection at the free end of the beam is

$$z = a\frac{E_1}{E_2}\frac{t_1^2 l^3}{t_2^3 w}\left(\frac{\gamma_1 - \gamma_2}{\lambda_1 t_1 + \lambda_2 t_2}\right)P, \tag{4}$$

where γ, λ, t, w, l, and E are respectively the thermal expansion coefficient, thermal conductivity, thickness, width, length, and Young's modulus of the beam layers (subscripts refer to the different materials) and P is the absorbed power. Equation (4) applies only in the limit $t_1 << t_2$ (t_1 is thickness of the magnetic film and t_2 is the thickness of the silicon cantilever). In addition, it is assumed that the temperature is constant over any cross section along the axis of the cantilever - this is a good approximation if t_1, $t_2 << l$. The constant a ranges from a value of 2, if power is absorbed near the end of the beam, to a value of 1.25, if power is absorbed uniformly along the beam.

The detection electronics are similar to those typical of optical chopping methods developed for photo-absorption experiments.[7] We monitor the deflections of the cantilever with a laser beam-bounce method. A diode laser source is focused onto the cantilever and reflected onto a split photodiode detector. This configuration enables us to detect both the deflection and the torque signals with the same apparatus. This system is commonly found in commercial AFM instruments and is capable of detecting 10 picometer vibrations under ambient conditions. The microwaves are applied to the sample by placing the cantilever in close proximity to a stripline resonator driven by a microwave sweeper. The microwave output from the sweeper is amplitude modulated by a square wave. The square wave also serves as the reference for the lock-in amplifier that measures the differences of the outputs from the split photodiode detector. The reflected wave from the microstrip resonator is monitored with the tuning scope. The microwave frequency is adjusted to obtain a minimum reflected wave amplitude as measured by the rf detector, indicating a maximum coupling of microwave power into the micostrip resonator.

We prepared samples by depositing 30 nm films of Co, NiFe alloy (81% Ni), Ni, or Au onto the flat sides of commercially available single-crystal Si cantilevers. Depositions were done in a diffusion-pump vacuum chamber with a liquid nitrogen cold trap. The base pressure was 3×10^{-4} Pa. The films were evaporated from alumina-coated W boats at a deposition rate of 0.15 nm/s. The cantilever dimensions were 2.5 μm x 49 μm x 449 μm with a deflection spring constant of 0.35 N/m, a deflection resonant frequency of 17 kHz, a torsion spring constant of 3.0×10^{-20} N·m/rad, and a torsional resonant frequency of 250 kHz.

Figure 2a shows the experimental configuration for measuring *M-H* loops with a microcantilever torque magnetometer (MTM).[8] Figure 2b shows two hysteresis loops for 10 nm Fe films measured with the MTM and with an alternating gradient magnetometer (AGM) for comparison purposes. In this experiment, we ramped up the sweep field H_0 to the maximum negative value of 7 mT before recording the data. The torque field H_T provided by the solenoid was kept constant at a level below 0.1 mT for the measurement. The torque signals decreased linearly with decreasing film thickness, i.e., magnetic volume. The magnetic moment m decreased from 8.9 x 10^{-10} A·m^2 for a 40 nm thick to 1.8 x 10^{-11} A·m^2 for a nominally 1 nm thick Fe film. For Fe film thickness from 40 nm to 4 nm the hysteresis loop was open, as expected, for an easy-axis hysteresis loop of a ferromagnetic film. A closer analysis of the data for nominally 2.5 nm thick Fe film shows an open hysteresis loop with a very small coercivity H_c of about 0.08 mT. The coercivity of the 40 nm thick Fe film was 2.5 mT, whereas the 20 nm thick film showed a coercivity of 2.1 mT, and the 4 nm Fe film 0.5 mT.

The experimental configuration for FMR with a μRTM is shown in Fig. 3a.[9] The torque T on the cantilever as measured by the lock-in amplifier is plotted versus the applied sweep field H_0. In this case about 68 μm of the cantilever was coated with a 30 nm thick NiFe film, which corresponds to a total magnetic volume of 1.1 x 10^{-10} cm^3. In order to find the torsional resonance frequency f_T of the cantilever, we swept the frequency of the oscillator providing the ac current to a torque coil prior to the measurement. The torsional frequency f_T was found to be 250.3 kHz. We used this frequency to trigger the pulse modulation of the microwave field and as reference to the lock-in amplifier. The input power to the microstrip resonator was 75 mW. The data are shown in Fig. 3b. Note that the direction of the torque is reversed upon reversing sweep field as e

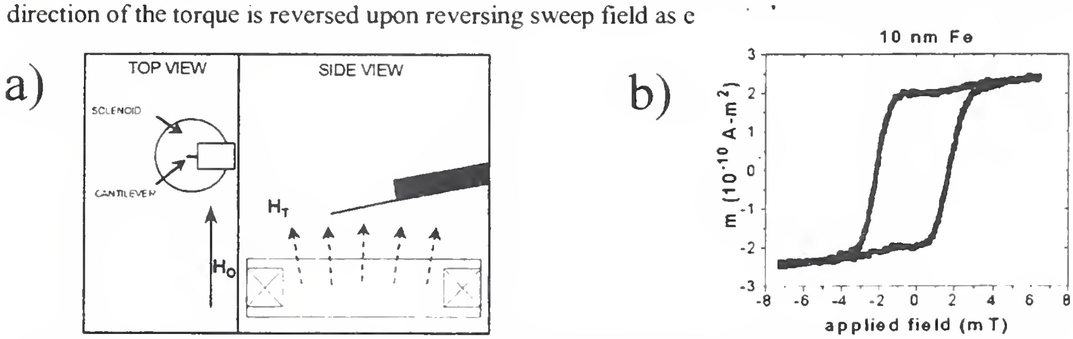

Fig. 2. M versus H measurements with a MEMS torque magnetometer. (a) experimental configuration. (b) magnetic moment versus applied field.

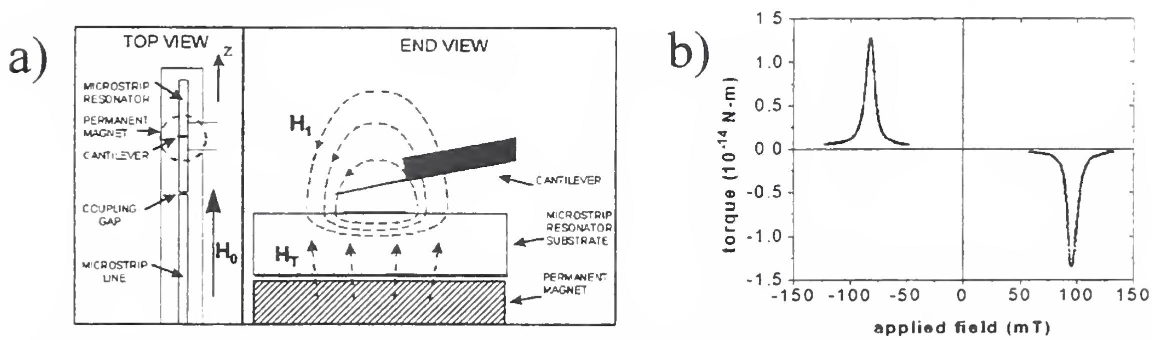

Fig. 3. FMR with a μRTM (a) experimental configuration. (b) cantilever torque versus applied field.

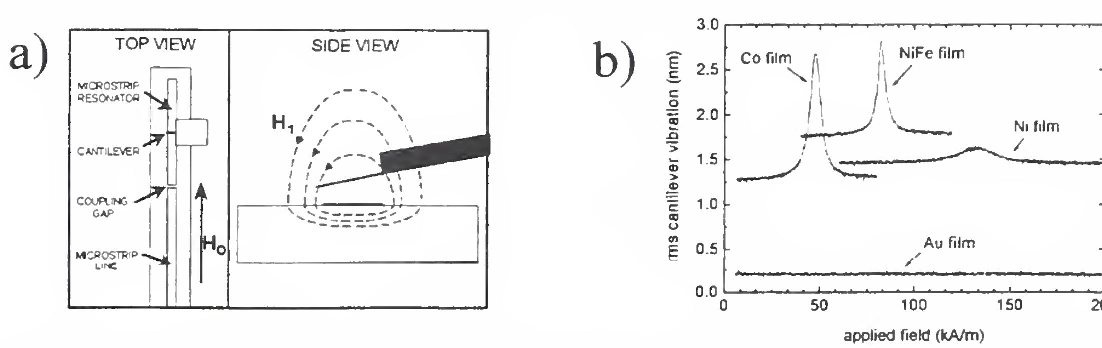

Fig. 4. FMR with a bimaterial calorimeter. (a) experimental configuration. (b) cantilever vibration versus applied field.

The experimental configuration for FMR with a bimaterial calorimeter[7] is shown in Fig. 4a. Figure 4b shows the FMR microwave absorption spectra of Co, NiFe, and Ni. We determined the peak locations and widths by fitting the data to Lorentzian absorption lines. The results agree well with data obtained using conventional resonant cavity detection of microwave absorption during FMR on similar samples.

System	Sensitivity ($A \cdot m^2$)
Commercial Systems:	
Torque magnetometer	10^{-12}
Alternating gradient magnetometer (AGM)	10^{-11}
SQUID magnetometer	10^{-11}
Fluxgate magnetometers	10^{-11}
Vibrating sample magnetometer (VSM)	10^{-9}
MR spectrometer	10^{-7}
NIST micromechanical systems (this work)	
micro resonating torque magnetometer:	
current	10^{-16}
potential MEMS optimization	10^{-18}
micromechanical FMR calorimeter:	
current	10^{-12}
potential MEMS optimization	10^{-16}

units: 1 $\mu_B = 10^{-23}$ $A \cdot m^2$, $(10\ nm)^3$ Co = 10^{-16} $A \cdot m^2$, and 1 emu = 10^{-3} $A \cdot m^2$

The table to the left summarizes reported sensitivities for several types of magnetometers. The commercial systems listed here are for typical instruments designed for routine measurements of relatively large samples. In general, these instruments have large detector volumes required for accommodating larger samples. One of the main advantages of integrating a sample with a detector, as is the case for the MEMS magnetometers discussed in this paper, is that the sample volume and the detector volume are nearly the same. It is difficult to do this with commercial systems for very small samples. In addition, some commercial systems are not well suited for measurements of low-moment samples because of electronic noise sources or instrument design.

The sensitivity levels afforded by MEMS based magnetometers make them excellent candidates for measurements of ultra thin magnetic films. For a magnetic film that is 100 μm on a side we expect to be able to detect sub-monolayer thicknesses. MEMS magnetometers are an enabling technology for future combinatorial studies on the effects of composition, deposition conditions, and post-deposition treatments including corrosion studies. For example, an array of μRTMs fabricated into the surface of a silicon wafer can be used to study not only magnetic characteristics but mechanical and microstructural characteristics of thin films, as well, as a function of temperature, composition, and magnetic field gradients over the wafer. Mechanical parameters including residual and non-uniform stress can be determined from the bending of coated cantilevers and the microstructure of the films can be studied with TEM if the films and the cantilevers are thin enough.

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The Validation of Fourier-Transform Microwave Spectroscopy for Trace-Gas Analysis

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There is strong interest by regulatory agencies and automobile manufacturers, motivated in large part by increasingly stringent emission standards, for measurement tools capable of quantifying various hydrocarbons, oxygenated hydrocarbons, etc., in automobile exhausts in near real time with sensitivity comparable to presently used gas chromatographs, i.e. nmole/mole. Concentration measurements of the exhaust-gas composition also potentially provide feedback on the complex chemistry in the engine and exhaust system, which may be used to improve fuel formulations and engine performance and reduce emissions. Here, we describe the technique of Fourier-Transform MicroWave (FTMW) spectroscopy, which is a high sensitivity technique (better than µmole/mole, i.e. 1 ppm) with near real-time response (down to 1 s) and 100 % certain chemical identification. The development of FTMW for gas analysis builds upon a long history at NIST in the quantitative analysis of gas mixtures, which includes standard reference gas mixtures, and more recently the development of a quantitative infrared spectral database of common air pollutants (Chu *et al.*, 1999).

FTMW spectroscopy was originally developed approximately 20 years ago by Balle and Flygare (1981) for the measurement of the microwave rotational spectra of trace exotic chemical species, such as weakly bound dimers, hydrogen-bonded complexes, diatomics molecules ablated from refractory materials, and free radicals. The high sensitivity of the technique and its unprecedented accuracy in species identifications motivated the beginning of an effort to assess the potential of FTMW spectroscopy for the quantitative chemical analysis of complex gas mixtures. Initial studies along these lines by Andresen *et al.* (1994) and Lovas *et al.* (1994) demonstrated the ability of the technique to deliver a linear response for a single trace gas impurity in a nitrogen gas stream. Since that time we have demonstrated the generality of the technique for the potential quantification of a variety of impurities in nitrogen or rare-gas streams at concentration levels less than 1 µmole/mole. Some of these chemical compounds relevant to automobile exhaust which we have studied are listed in the Table I below. Of particular interest to the automobile industry is quantification of various oxygenates (aldehydes, ketones, ethers, and alcohols) potentially present in the exhaust during the first few minutes after the engine is started, when significant undesirable emissions are generated. Based on laboratory measurements of ideal samples, FTMW spectroscopy has the ability to detect and potentially quantify the oxygenates listed in Table I.

Table I. Oxygenates detected by FTMW Spectroscopy

Aldehydes	*Ketones*
Formaldehyde	Acetone
Acetaldehyde	Methyl ethyl ketone
Propionaldehyde	*Alcohols*
n-Butyraldehyde	Methanol
Valeraldehyde	Ethanol
Methacrolein	*Ethers*
Benzaldehyde	Methyl *t*-butyl ether (MTBE)
p-Tolualdehyde	Ethyl *t*-butyl ether (ETBE)
Acrolein	*t*-Amyl methyl ether (TAME)

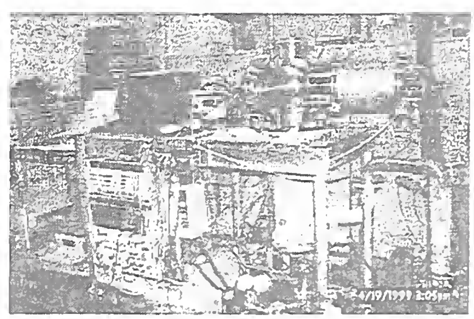

Figure 1. Photograph of FTMW Spectrometer

Figures 1 and 2 show a schematic diagram and a photograph, respectively, of one of the FTMW spectrometers at NIST. Briefly, a molecular beam of a sample is injected coaxially into a high-*Q* Fabry-Perot microwave resonator using a pulsed-molecular-beam valve. Once the molecules reach the center of the cavity, a short (approximately 1 µs) pulse of microwave radiation resonant with one of the TEM_{00} modes of the cavity is applied to the molecular beam. If the molecules have a resonance overlapping the 500 kHz bandwidth of the cavity, a macroscopic polarization is induced. The electric-field due to this polarization is detected as a function of time using a super-

heterodyne receiver. The detected signal is digitized and then Fourier-transformed to obtain a spectrum. Such a spectrum is illustrated in Figure 3 for the $J = 2 - 1$ rotational transition of $OC^{36}S$ in natural abundance in a 1 % by volume carbonyl sulfide in argon gas mixture. The "Doppler-doublet" structure is a consequence of the unidirectional molecular beam interacting with the two traveling wave components of the cavity standing wave. It should be noted that the technique is not directly applicable to molecules such as benzene, napthalene, and carbon dioxide, which lack a permanent electric dipole moment, and light hydrides such as HF or OH, which do not have any absorption lines in the microwave spectral region.

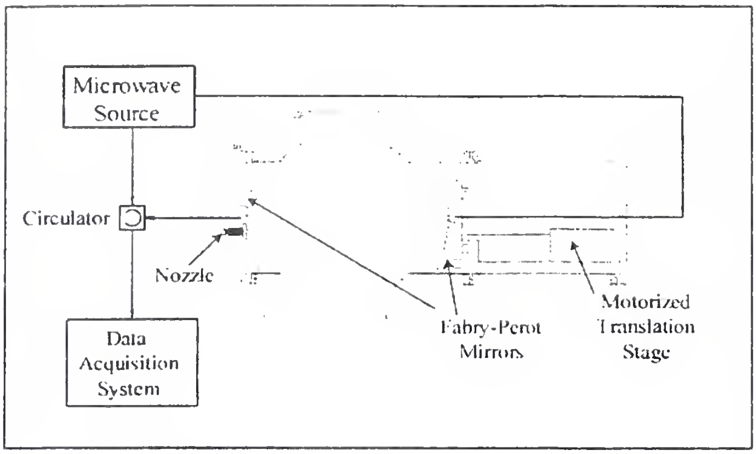

Figure 2. Schematic Diagram of the FTMW Spectrometer

The high spectral resolution (5 kHz FWHM) relative to the approximately 10 GHz operating range of the instrument and the unique qualities of the rotational spectrum of a molecule give the instrument effectively 100 % species selectivity. This selectivity is illustrated in Figure 4 for the structural isomers pinacolone and pinacolyl alcohol. The instrument also provides a rapid, near-real-time response. The time response of the instrument is limited by the 5 Hz to 10 Hz nozzle pulse rate, the flow rate of the gas to the nozzle, and the gas-line passivation. A typical time-response is shown in Figure 5 for a sample of acetaldehyde in N_2 with Ne/He added for increased sensitivity. We have more recently demonstrated the capabilities of FTMW spectroscopy for the detection of chemical warfare agents. Figure 6 shows survey microwave spectra for the nerve agents Sarin and Soman as recorded using a FTMW spectrometer established in a surety laboratory at Aberdeen Proving Grounds.

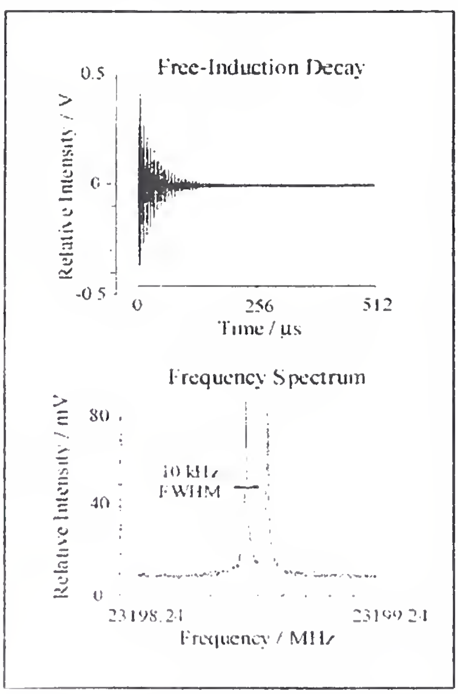

Figure 3. Free-induction decay signal and its Fourier Transform

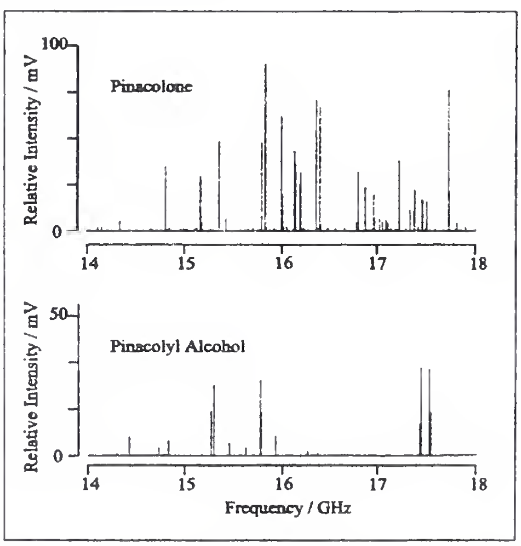

Figure 4. FTMW spectra of the two structural isomers, pinacolone and pinacolyl alcohol.

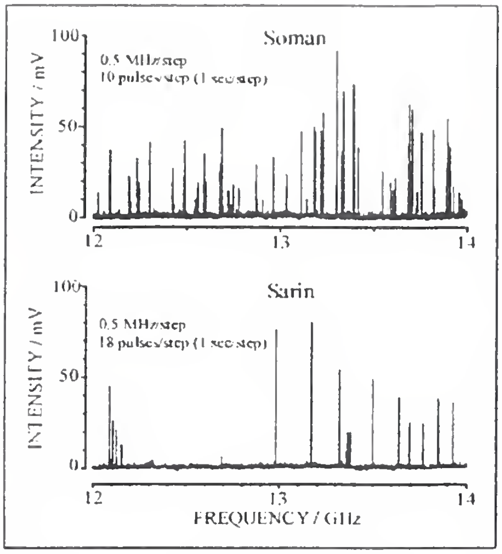

Figure 5. Suvey FTMW spectra of the nerve agents Soman and Sarin.

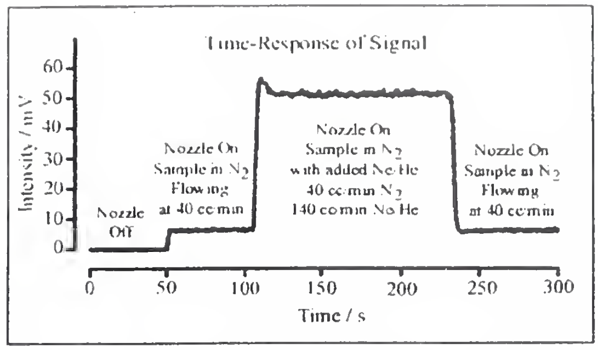

Figure 6. Illustration of the time response of the spectrometer for a sample of acetaldehyde in N_2 with Ne/He added.

Present efforts are directed at validating FTMW spectroscopy for the quantitative analysis of complex mixtures of gases, such as several trace gas impurities in air. Of particular concern is gas condensation and non-thermal equilibrium in the supersonic nozzle expansion, processes which are expected to be more pronounced in complex gas mixtures. In addition, we will be examining in more detail the linearity, frequency variation, effects of humidity, and short and long-term reproducibility of the instrument, as well as addressing the needs for gas-mixture standards.

As part of this effort we have tested the ability of FTMW spectroscopy to positively identify a series of trace impurities in a nitrogen gas sample. The researcher performing the measurements and analysis was not aware of the contents of the sample, except that it consisted of one or more components from a selected group of 16 oxygenates. FTMW was able to correctly identify all the components of the gas mixture, with no false positives. In addition, by comparing the signal intensities to known standards when available, consisting of a single trace gas in nitrogen, reasonable estimates for the concentrations of the impurities in the unknown were obtained. The results from this study are summarized in Table II. It is important to emphasize the preliminary nature of these results. The unknown concentrations were assigned with only one calibration standard and further work is required to validate the instrument response function under the present operating conditions.

Table II. Blind unknown analysis.

Trace component	*S/N after 1 min of signal averaging*	*Concentration determined (μmol/mol)*	*True value (μmol/mol)*	*Standard used (μmol/mol)*
Acetaldehyde	16/1	0.086	0.202 ± 0.5 %	13.0
Ethanol	170/1	60	60.3 ± 0.2 %	70.54
Ethyl-*t*-butyl ether	10/1	---	5.19 ± 0.5 %	---
Methyl ethyl ketone	44/1	---	5.22 ± 0.2 %	---

The results in Table II demonstrate the potential of FTMW spectroscopy for trace gas analysis of multicomponent mixtures. For instance, with 1 min of signal averaging FTMW appears capable of detecting acetaldehyde and ethanol at concentration levels of approximately 5 nmol/mol (5 ppb) and 0.4 μmol/mol (0.4 ppm). These preliminary successful results certainly show the promise of FTMW for automobile emissions monitoring, and are a motivating force for our continuation of this effort.

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Measurement Protocols for Characterizing the Appearance of Automotive Coatings

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I. Introduction

The appearance of an object is the result of a complex interaction of the light field incident upon the object, the optical characteristics of the object, and human perception. For a variety of manufactured products, the measurement of the appearance indicates the quality and acceptability of the products. For example, color and appearance of automobiles is reported to be a major factor in about half of car purchases [1].

Coatings for a variety of functions are ubiquitous, with the Census Bureau estimating that shipments in the early 1990's by U.S. manufacturers of coatings had a value of $11.5 billion. A less obvious aspect of coatings is the diverse science and technology behind them. Coatings can be described by their appearance, such as metallic or pearlescent, and by their functionality, such as corrosion protection or photosensitivity. Pigments are being manufactured with new and unique appearance attributes, and the traditional measurement techniques are not always capable of adequately characterizing the color attributes or correlating them with visual perception. For example, gonioapparent coatings (metallic and pearlescent) exhibit differences in their color and appearance with changes in the illumination or viewing angle, or both [2]. Therefore, the traditional single geometry measurement is not capable of characterizing the perceived color variations on gonioapparent coatings. These coatings are very important to the generation of many new and unique effects used in the printing of currency, formulation of cosmetics, and application of paint for automobiles. For example, metallic coatings were developed in the 1940's and by the 1980's about 70% of all cars had metallic finishes. With the support of the Advanced Technology Program at NIST, we are conducting a series of experiments in order to characterize these coatings. We intend to determine the minimum set of illumination and viewing geometries needed to accurately characterize the color of these coatings utilizing the bi-directional reflectance distribution function. This research program is directed to answer industry demands for standards and accurate measurement protocols for production and quality control of these coatings.

II. Characterization of Gonioapparent Coatings

Table 1 shows a comparison of the optical characteristics of conventional absorption and gonioapparent coatings. For all of these coatings, the front surface is a clear, smooth coat. The reflective properties of this overcoat are investigated at the specular geometry. The perceived color in absorption pigments is due to absorption and diffuse scattering and is independent of geometry. In contrast, the primary interaction of light with metal-flake pigments is specular reflection from the flakes, and the perceived brightness depends on the geometry. Pearlescent pigments usually consist of thin metal oxide layers on transparent mica platelets, and their perceived chroma, hue, and brightness depends on both the incident and viewing angles.

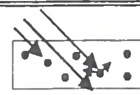
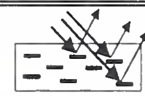
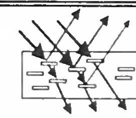
Type of pigment	Absorption	Metallic	Pearlescent
Optical principle of pigments (first order)	 Scattering	 Specular reflection	 Thin-film interference
Perceived chroma and hue	Independent of geometry	Independent on geometry	Dependent on geometry
Perceived brightness	Independent of geometry	Dependent of geometry	Dependent on geometry

Table 1. Optical Principles of absorption, metallic, and pearlescent pigments

The bi-directional reflectances of a series of pearlescent samples with different colors for the pearlescent and base coats were measured using the Spectral Tri-function Automated Reference Reflectometer (STARR) at NIST [3] with a minimum expanded (k=2) uncertainty of 0.4 % for the wavelength range of 380 nm to 780 nm. Figure 1 shows the measured reflectance for one sample with a bright red base coat and red-blue pearlescent coat for the wavelength range of 380 nm to 780 nm, illumination angle of 45°, and viewing angles of -15°, -35°, and 65°. As seen in Fig. 1, the measured spectral reflectance depends on the viewing angle. The red-blue component from the pearlescent coat is observed for the wavelength range of 380 nm to 780 nm and at geometries near specular such as 45°/-35°. The red component from the base coat is observed for the wavelength range of 580 nm to 780 nm and at geometries far away from specular such as 45°/65°. Furthermore, the measured reflectance at geometries, like 45°/-15°, is a mixture of the two components.

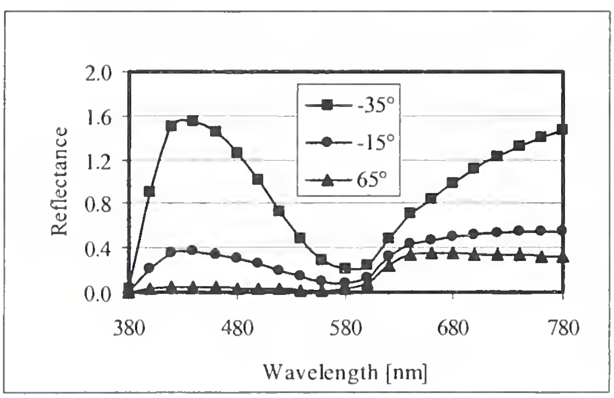


Fig. 1. Bi-directional reflectance of a bright red base coat and red-blue pearlescent coat sample for the illumination angle θ_i = 45° and the viewing angles of -35°, -15°, and 65° with a maximum expanded uncertainty (k=2) of 0.7%.

Figure 2(a) – (c) shows the CIE ab angle dependent color travel for this sample at incident angles of 15°, 25°, 45°, 65°, 75° and viewing angles of –80° to 80° at 5° steps. The color travel observed here results from the different scattering mechanisms that are present in these samples. The directional reflected light from pearlescent coatings is composed of a specular component from the clear coat, a component from the pearlescent pigments, and a diffuse component. The

clear coat reflects light in a specular manner from the clear coat/air interface, and is relative colorless ($a \approx 0$, $b \approx 0$). The specular component results in a measurement of the glossiness of the clear coat. Pearlescent pigments, which are aligned roughly parallel to the surface, reflect part of the light in a specular manner. The part that is not reflected is transmitted to the next layer, where further specular reflection occurs. This process results in a distribution of scattering angles near the specular geometry where the color of the pearlescent component is observed. For incident angles close to the normal of the sample (15° and 25°) shown in Fig. 2(a) and viewing angles close to the specular geometry, the blue pearlescent component is seen. Finally, the pigments in the base coat reflect light diffusely at all angles. The color in the base coat can be observed at all geometries but is dominant at geometries far away from the specular condition. As shown in Fig. 2(a) – (c), the diffuse component of the bright red basecoat component is accessed at grazing angles for the small incident angles and at large incident angles (65° and 75°). Figure 2(b) shows an intermediate incident angle of 45°; this geometry starts to show the interaction of both components resulting in a purple color and becoming more pronounced at near specular geometries for grazing angles as seen in Fig. 2(c). Since the measurements cluster in three different groups (pearlescent, basecoat, and the interaction of both components), we could select a subset of measuring geometries that will provide a complete view of the perceived color variations observed in the pearlescent coatings.

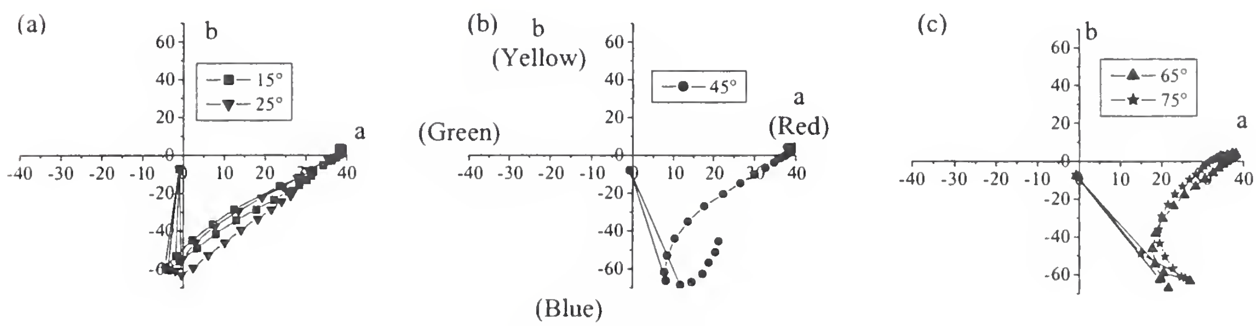


Figure 2. CIE ab angle dependent color travel for a red-blue pearl coat and bright red basecoat sample at the incident angles of (a) 15° and 25°, (b) 45°, and (c) 65° and 75° and viewing angles of -80° to 80° at 5° steps.

III. Summary and Future Work

This paper describes a systematic study on gonioapparent coatings in order to develop standard measurement protocols for the accurate color characterization of these coatings using an understanding of their scattering mechanisms as a guide. Measurements of the bi-directional reflectances are a powerful technique for characterizing the scattering mechanism of gonioapparent coatings. We conclude that the directional reflected light from pearlescent coatings is composed of a specular component from the clear coat, an interference component, and a diffuse component. The clear coat reflects light in a specular manner, similar to a mirror. Interference pigments reflect only part of the light in a specular manner. The part that is not reflected is transmitted to the next layer, where further specular reflection occurs. This process results in a distribution of scattering angles near the specular geometry. The reflection color of the interference component is seen at geometries close to specular. Finally, the absorption

colorants in the base coat reflect light diffusely at all angles. The color of the absorption pigment in the base coat is observed at geometries far away from the specular condition.

We plan to investigate the relationships of the microstructure properties and the optical reflectance properties of gonioapparent coatings. The underlying microstructure properties such as surfaces roughness, particle size and density determine the optical scattering distribution, which result in the perceived appearance. We intend to relate the microstructure properties to the optical scattering properties to develop a methodology for predicting the appearance of coatings.

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Near Net Shape Processing Theory

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Abstract. When a new net shape discrete part (i.e. a part made in a die or mold) is to be made, the sequence of manufacturing steps must be specified (i.e. processing level I) and the method(s) of focusing energy onto the workpiece within each of those steps (i.e. processing level II) must be specified in some detail before the feasibility of the part design can be established, the detailed design of the tooling can be started or the process control strategy can be planned. These activities are the processing function. This paper focuses on the "Level II" processing issues of the processing function. The net shape processes tend to present greater risks than the non-net shape processes in that the actual performance in terms of the end quality of the piece part and the efficiency of the manufacturing process are less predictable. The premise of this paper is that the net shape processes need a coherent, clearly articulated processing theory based on first principles that is recognized as a legitimate engineering discipline in its own right. Basing the processing of the net shape parts on theory borrowed from other disciplines is not adequate. The net shape processes are characterized by metrics, connectivity, geometry, redistribution, remoteness and non-uniformity. Examples are provided illustrating how these attributes differ from the non-net shape processes and how those differences complicate the processing problem. The paper then presents the five basic steps of such a processing theory. These are: (1) Define the product requirements from the customer's perspective. (2) Identify the relevant transformation characteristic. (The transformation characteristic is a measurable characteristic, such as the strains in a sheet metal stamping, that can be effected through the application of energy.) (3) Create a state map of the transformation characteristic necessary to achieve the product requirements. (This could be the solidification pattern of a casting showing where the solidifying fronts must meet.) (4) Calculate (from first principles) the energies required to achieve the mapped states of the transformation characteristic, e.g., how muc h heat must be extracted from each sq. cm. of casting surface to put the solidification front in the right place. (5) Design the energy applicators in the die or mold to impose the interface energies onto the piece part material, e.g., position and size the water cooling lines in a pressure die casting die. A step-by-step processing algorithm can be developed for any specific net shape process by expanding on these five steps. Such a procedure will facilitate the synthesis of the design of the critical energy effecting elements and the processing control of those elements. Such a synthesis approach is fundamentally different, and can lead to greater optimization, than can designing by experience, or rule, and then analyzing to determine the performance of the design. Once such a processing algorithm is in place and recognized, it would have significant ramifications on the direction of research projects in the subject area, educational programs in the area of manufacturing engineering and the organizational structures and job definitions within manufacturing operations.

Nontraditional Machining Technologies in the Context of Automotive Manufacturing

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Extrude Hone Corporation is an innovative enterprise dedicated to the development and implementation of advanced manufacturing processes including nontraditional machining, finishing and measurement technologies. Process thrusts include abrasive flow machining/finishing/deburring; electrochemical machining/deburring; ultrasonic machining and orbital polishing; solid free form manufacturing of metal tools and parts; and surface/edge/ dimensional measurement. Primary markets include dies and molds, aerospace, diesel, automotive, medical pharmaceutical, food and semiconductor industries. Extrude Hone has recently completed a NIST ATP program directed at flow control machining in automotive engines and is currently engaged in a NIST ATP effort utilizing rapid metal tooling technology to produce tooling for lost foam castings.

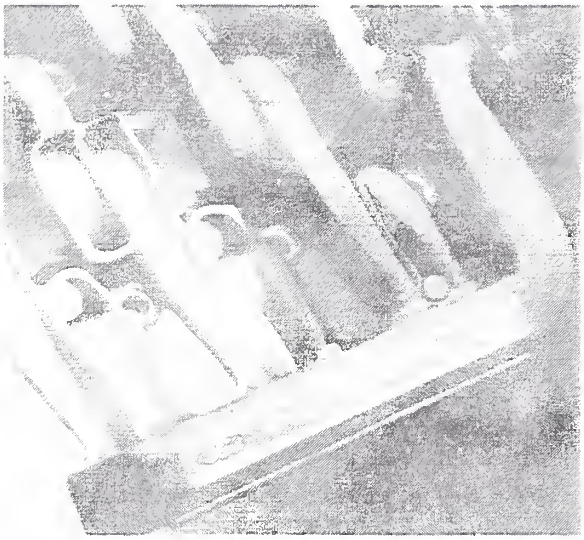
The five-year, $11 million cost-shared program directed to enhancing the air flow passages of automotive components teamed Extrude Hone, Ford Motor Company, General Motors, University of Pittsburgh and the University of Nebraska at Lincoln. The objective of the research was to develop abrasive flow machining and sensing techniques to enable automotive flow passages to be processed to a target airflow which is measured *while the component is being machined.* The central concept of flow control machining is one of machining to *function* rather than to *geometry*

The focus of the ATP-funded project was the engine passages that control the volume of air ingested. These passages are too complex to be economically machined by conventional machining or grinding and are typically cast. The cast cavities vary in shape and position and have rough, irregular surfaces. These variations have significant impact on the performance, fuel efficiency and emissions of automotive engines. The ability to control these variations *in-situ* would enable building higher performance, more fuel efficient and cleaner burning engines at lower cost and in lower economical production volumes than currently possible.

The project depended on an especially strong experimental and statistical component. Extensive data collection on, before and after air flows of specific component test pieces coupled with continuous process flow data provided a large information base that, with appropriate analysis techniques, resulted in a derivation of a correlation between air and AFM media. Acoustic emission sensing capabilities were used to monitor the flow rate of the machining medium in real time to the required resolution. A high-speed data acquisition system for acoustic emission monitoring and flow control was developed. Extensive experimentation was performed to correlate changes in flow resistance to characteristics of the AE signal. The research showed that an analysis of the outputs from the AE signal did indicate when to stop machining for flow control processing of intake manifolds.

The resultant flow control machining (FCM) cell is comprised of multiple stations for tracking, inspecting airflow, processing, and cleaning. All data was collected and stored automatically. Moreover, the stations are all connected to the local area network (LAN) so all of the data is easily accessible by managers and engineers. By monitoring the results of the inspection stations and correlating these with the information from the processing station, it is possible to determine what action needs to be taken to maintain control of the machining process. In early stages of the project, this proved especially useful.

A manifold is comprised of twelve runners, or six pairs consisting of a long runner and a short runner. The initial goal of the effort was to achieve increased airflow on the overall component. One way of approaching flow control machining is to process a given passage until it achieves the target flowrate. At this point, this passage would be blocked and processing on it would stop. Although this would appear to be a very efficient approach, it is not always feasible for every component. Another method is to sequentially open blocked passages so that the passages require the most machining are open longer than those that do not. By choosing the appropriate point to open each passage, at the end of the cycle the passages are evenly processed. Not only does this improve airflow on the overall component, but also balanced airflow among the pairs of runners, resulting in a longer lasting product.



Ford selected their SVT 2.5L V-6 engine to test the capabilities of FCM. Over 30,000 components were processed during the scope of the effort. Port and manifold runner variability measured less than 2% compared with an industry-nominal of 5% variability, significantly boosting airflow. Ford reported increased customer satisfaction, citing Extrude Hone as a major contributor to this index.

Through the cooperation of industry and academia, many innovations were realized that are of significant benefit to a wide range of companies and individuals. Because of the success of this project, automotive manufacturers are becoming more open to the benefits of the AFM process. It has been shown that the process can be used effectively to process high volumes of components consistently. The company is continuing to process engine sets developed under this program. Moreover, the infrastructure developed to effectively manage the project has served as a model for future work. As this project was drawing to a close, an automotive manufacturer asked for assistance in the enhancement of a component of one of its models that has high visibility in the performance car market. The same data collection and reporting scheme was quickly and successfully applied to the new job. It is anticipated that the successful integration of the numerous areas of the project will be a major selling point as similar large-scale projects are sought. In addition, the company is in development with a new cylinder head and intake manifold program with a third automotive manufacturer.

Academic partners have also benefited from the innovations of this program. Several graduate degrees (both MS and Ph.D.) were earned with research relating to this effort. Development of the neural net and the study of a new tracking system provided topics for one local university whose students worked closely with the company and the process. Another performed research in the areas related to acoustic emissions and the integration of AE to flow control machining. Two students spent a summer working with the process and performing research for their master's theses. Development of the tracking system has created numerous business opportunities and the proposed system is now widely-used and considered the state of the art. A patent application has also been made by another university partner. The research conducted to date has contributed much to the understanding and control of the AFM process and will doubtless continue to do so as it leads to further research into different areas.

The program also initiated a study by NIST economist Mark Ehlen, Ph.D. entitled Economic Impacts of Flow Controlled Machining Technologies: Early Applications in the Automobile Industry. Modeling the five-year implementation path of the FCM process, the report concludes that "This additional production would increase annual domestic product (GDP) by an estimated $142 million." With the new federal regulations to significantly reduce emissions on small engines, the economic and social impact could be even greater.

The company consistently met automotive quality requirements for production component processing while simultaneously performing process research. Rigid delivery schedules were met and changing customer requirements were satisfied. Significant market exposure was achieved. The engine was named one of the ten best engines by Ward's Auto World for two years running. Spin-off feature articles describing the developed technology were published.

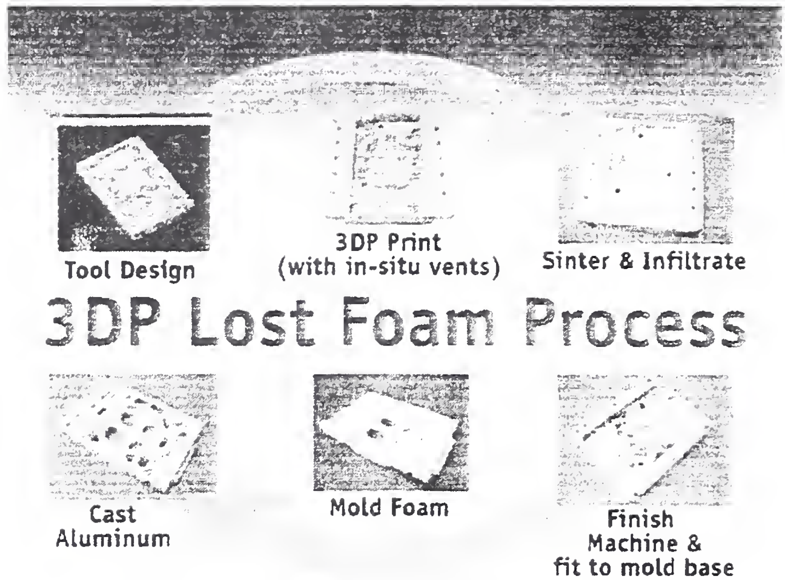
Automotive, truck and aircraft engine builders as well as manufacturers of any product relying on precision orifices will benefit from the unique manufacturing technology to economically produce more efficient, higher performance and in many cases more environmentally responsible products (such as more fuel efficient, cleaner burning engines. The company plans to continue to develop equipment and media with better productivity, to study and document process effects on emissions, and to translate the developed technology into other application areas.

Extrude Hone Corporation is currently working with General Motors Powertrain to develop the three-dimensional printing (3DP™*) process for making the tooling to produce foam patterns for manufacturing complex cast aluminum automotive components like cylinder heads, intake manifolds and transmission housings. 3DP is a rapid prototyping process which works along the same lines as an ink-jet printer, using metal powder to "build" the part from a CAD file. The component is then sintered and infiltrated to produce a fully functional part, not just a prototype. Technical challenges include scaling up the 3DP machine to produce production components; developing a 3DP material system for lost foam castings including porous surface capability; reducing process time by a factor of ten; reducing the time required to manufacture automotive tooling by at least a factor of two; and developing low-cost sintering and infiltration capabilities.

General Motors has adopted the lost foam casting (LFC) process to manufacture the cylinder heads with greater accuracy and lower cost than conventional techniques. LFC is the most cost-effective method of providing cast cylinder heads with the complex geometry required for the high power density, light-weight engines required today. The major limitation of the LFC process, however, lies in the design and manufacture of the tools to produce the foam patterns. The lead times and costs of tooling are substantial and changes are not easily incorporated. *The goal of the proposed effort is to reduce the time required to produce the tooling by at least a factor of two.* Present lost foam casting tooling typically requires over fifty components configured into a complex assembly due to lost foam casting process requirements of numerous connections for steam, pellet insertion and moisture vacuum. Additional constraints of present manufacturing methods not being capable of producing geometrical configurations such as reentrant shapes, undercuts and contoured internal passages compound the tooling complexity.

The focus of this effort lies in the development of an alternate method for constructing LFC tooling that eliminates the machining of the mold contours and the time consuming drilling of the steam holes. The technical approach involves repeatedly printing layers of bonding material on a powder coated surface to build up a part shape from the mathematical model. This is the three dimensional printing "rapid prototyping" concept applied to metals rather than paper or polymers. In this effort, the process would not only build a prototype set of tooling, but would build the multiple sets of production tooling required for the high volumes of castings required by the automotive industry.

The 3DP process offers enormous potential for totally changing the tooling design and manufacturing paradigm with its unique capabilities. The 3DP process offers the ability to produce geometrical configurations in a single component that can replace numerous assembled components with complex contours and passages. Additionally, the process can potentially generate geometrical configurations such as porous or foam-like surfaces impossible to practically create by any other means.



Accomplishments to date include:

- Extensive experimentation with a wide range of material systems and techniques
- Completed design of multiple nozzle head; testing in progress
- Designed and built pre-prototype machine capable of handling the large tooling blocks required
- Investigated specifications for a scaled-up furnace
- Demonstrated the ability of the process to produce selective porosity, potentially eliminating the cost and time required to manually drill steam holes

Work will continue to develop the 3DP™ technology to meet the size and accuracy requirements specified by GM. A prototype system incorporating the developments will be designed and built.

The 3DP process is a strong enabler for production intent and this project will serve to develop hydrohead lost foam casting tooling in a manner that will be capable of being applied to mass production. The development of the lost foam tooling industry is just really beginning. There are less than a dozen tooling firms that General Motors considers qualified to build lost foam tooling. Success of this development program would dramatically reduce the cost and lead times and extend the design flexibility of LFC components, substantially accelerating the substitution of aluminum and reduction of weight in U.S.-built automobiles and trucks.

The potential applications of this technology are nearly endless. While the focus of the effort is to develop a "breathable" metal material for the transmission of steam, such a material could be used where a flow of liquid or gas to the surface was required, such as in gas lubricated bearings, high temperature processing of materials where cooling is required, rocket nozzles, and so forth. A second area of application would be where a high temperature alloy was to be infiltrated by a secondary material to provide additional strength or thermal conductivity. The process can also be used to make materials with different layers of metals to control thermal or electrical conductivity, if desired.

Potential program benefits include a dramatic reduction in cost and lead times as well as a substantial acceleration in the use of aluminum and subsequent reduction of weight in U.S.-built automobiles and trucks. ATP funding is essential to the timely development of this technology, providing the essential trigger to accelerate the development and commercialization of low cost, rapidly produceably, highly flexible and accurate tooling—the principle constraint in the expanded use of light-weight, low cost lost foam casting components.

The Next Generation Industrial Production Process for High-Density Powder Metal Products

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Bill Jandeska, GM Powertrain
Terry Cadle, GKN Sintered Products
David Score, Delphi

The objective of this project was to mature Dynamic Magnetic Compaction (DMC) technology from a "laboratory curiosity" into a robust industrial process suitable for high volume automotive component manufacturing. The motivation for the project was high-density compaction of powder materials. Conventional powder metal processing starts with compaction of the powder into a net or near net shape "green" part using dies and a mechanical compaction press. The green part is then sintered in a reducing atmosphere to bond the powder particles together and provide the desired material properties. Conventional pressing of ferrous powders leaves significant porosity in the green part. This porosity remains after sintering and results in reduced material properties when compared to wrought or forged materials which don't have porosity. The cost of production using this powder metal process is, however, attractively low with when compared to machining products from wrought or forged blanks. High density DMC compaction promised to provide material properties close to those of wrought and forged materials, but with the low cost structure of the net shape single press, single sinter powder metal process. Successful development of DMC would lead to the application of low cost powder metal processing to high performance, high cost, components such as transmission gearing.

The project focussed on two demonstration components, a ductile cast iron transmission ring gear, and a composite iron ignition core. The gear is currently machined from a cast blank and the ignition core is made by stacking thin steel lamina. Both products are relatively expensive using current production technologies and could be significantly lower in cost if produced using powder metal.

Transmission gearing cannot currently be made with powder metal processes because of the residual porosity and the consequent reduction of mechanical properties. Strength, ductility, and fatigue properties are all critical in gear application and all are significantly reduced by porosity. It was thought that densities of at least 7.5g/cm^3 would be required to achieve acceptable performance. Conventional powder pressing can achieve only about 7.2g/cm^3.

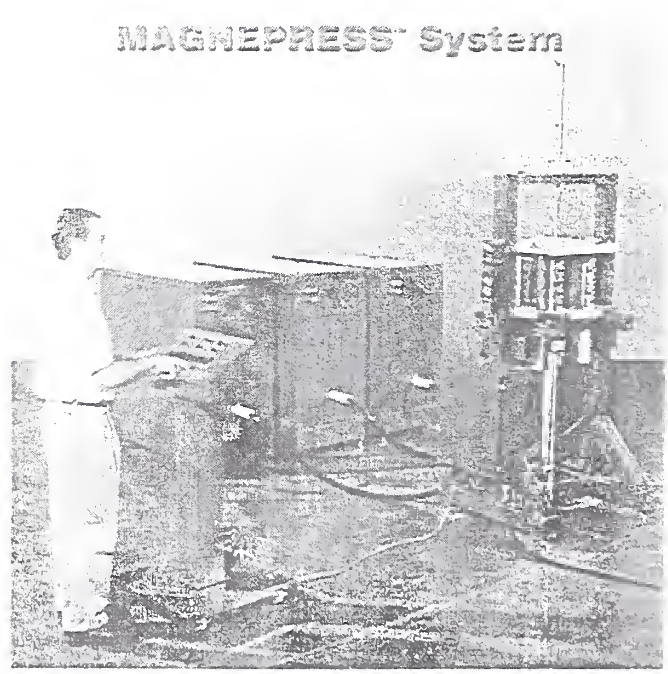
A DMC process was developed which produced densities in 4000 series steels as high as 7.6g/cm^3 in the gears. The mechanical properties approached that of wrought 4000 series steels and met or exceeded that of the cast material now used. Production costs estimates showed a significant cost reduction over the process currently used.

Transmission gearing also presents significant geometry challenges for powder metal processing. The geometry requirements are demanding (AGMA Class 9 or better). The porosity (particularly non-uniform distribution of it in the part, and residual stresses introduced by compaction result in part distortion during sintering and heat treating. Secondary steps, such as restrike or coining, are often required to recover geometry in conventionally pressed parts. Our goal was to achieve the required geometry without any secondary steps. This required very low residual porosity and cylindrically symmetric distribution of porosity and residual compaction stresses. We were able to demonstrate that this is achievable with the DMC based process.

Ignition systems are evolving to "coil at plug" implementations in which each spark plug has it's own ignition coil. Because of limited space in the engine compartment, there is great pressure to reduce the size and increase the efficiency of ignition coils for this system concept. Conventionally pressed powder metal cores do not meet the performance requirements and laminated cores are costly to produce. The goal here was to achieve much higher density and, therefor, higher performance with powder cores using DMC, while retaining the low cost structure of the powder metal process. Geometry is less demanding for this product, but diameter tolerances have a significant impact on final product size.

A pilot scale production system for ignition cores was set up and capability studies for were conducted. The process was shown to be capable and robust, meeting all the quality goals required for full scale production. The production cost goals were met and the process has brought significant cost pressure to bear on laminated core cores. Delphi now considers powder cores and DMC as a production option for new ignition systems. DMC is now competing directly against laminates for this business.

The project was organized to simultaneously develop the process for making the products and the equipment to implement the process. A complete magnetic pressing system, capable of 15ppm production rates, was developed by IAP Research Inc and is now being marketed under the *MAGNEPRESS*® Systems trade name. These systems provide turnkey DMC capability.



The project goals were met. DMC high-density compaction technology was matured and demonstrated on two demanding, but different, products. The expected property improvements were realized. Industrial equipment to implement the process was developed and is now available commercially. The DMC process and DMC based products are now being bid competitively in the market place. Commercial success, as in any mature technology, now hinges primarily on our ability to meet the cost, quality, and schedule requirements of our customers.

Liquid Molding for High-Volume Automotive Production

David H. Stewart, Director, Stewart Automotive Research

1. Introduction. The automotive industry has shown many times that the application of aerospace composites to body-in-white structure can result in reductions in mass of up to 70%, while maintaining stiffness and crash performance; two recent demonstrations being the Automotive Composites Consortium's (ACC) Multimatic-built prototype (Fig. 1) and BMW's Z22 project. What is still missing from this work, however, is a viable method of producing these structures in a manner compatible with the high volume and quality control requirements of the automotive industry. Autoclaved composites provide excellent levels of performance, but require hand lay-up of the reinforcement and very long cycle times, making them totally unsuitable for manufacturing more that a few hundred parts per year. Over 70% of the composites used in the US auto market are SMC (sheet molding compound), in spite of the comparatively poor physical properties and quality control problems of the material. What SMC does offer is low cost and fast cycle times, and it is these two characteristics that are absolute requirements for an automotive process. Quality variability is accepted because of the cheaper tooling, faster lead-times, and design flexibility offered by plastic components, but it does limit the growth potential of SMC. The most promising alternative to these two methods are the liquid molding processes such as RTM (resin transfer molding) and SRIM (structural reaction injection molding), where a variable ratio pump injects a mixture of resin and catalyst into a closed mold containing a fiber preform. The limitation of this process is that as the fiber volume fraction of the preform rises from the 15-20% level common in SRIM to the 50-60% level of an aerospace composite, the time required to fill the mold rises exponentially. This severely limits the cycle times that can be achieved with liquid molding, as the resins must have a working time at low viscosity long enough to insure infusion and then rapidly crosslink or polymerize to a green strength sufficient to allow demolding, a process that can take 2-20 times as long as the working time. To use the fastest reacting resin systems, an infusion time of less than 15 seconds is required to provide a total cycle time in the 2-4 minute range that is considered necessary for automotive volumes.

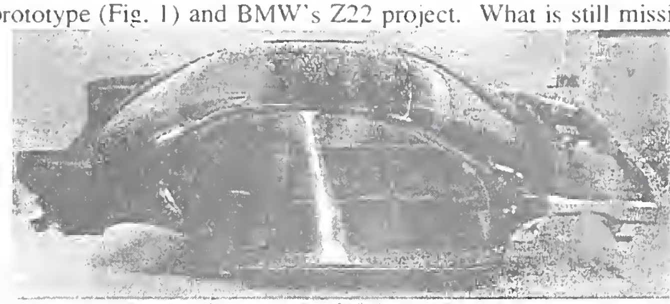


Figure 1. ACC Prototype.

2. Zoned Pressure Molding (ZPM). Stewart Automotive Research has developed a liquid molding process with the following goals in mind: aerospace performance, fast cycle times, repeatable quality, and low variable and capital costs. To achieve these goals the process must allow the use of high volume fraction performs, provide infusion times of under 15 seconds, allow programmable control over the resin flow, and be adjustable for variation in resin properties. An accurate simulation tool was also desired for use in optimizing the process. The ZPM molding process developed to meet these goals differs from RTM/SRIM mainly in flow path and tool construction. In RTM, the resin is injected into a closed tool and must flow through the preform to reach the perimeter of the part. In ZPM (Fig.2), a segmented upper tool half is constructed which can be actuated under hydraulic control. A compliant injection nozzle is mounted to one of the actuators and sealed to an elastomeric flexible top cover (FTC), which seals the resin between the preform and the sliding mold sections. Vacuum is pulled in the cavity to eliminate air entrapment. This arrangement allows the resin to be distributed uniformly across the preform, and then infused through the thickness direction, providing a flow path orders of magnitude shorter than in traditional liquid molding.

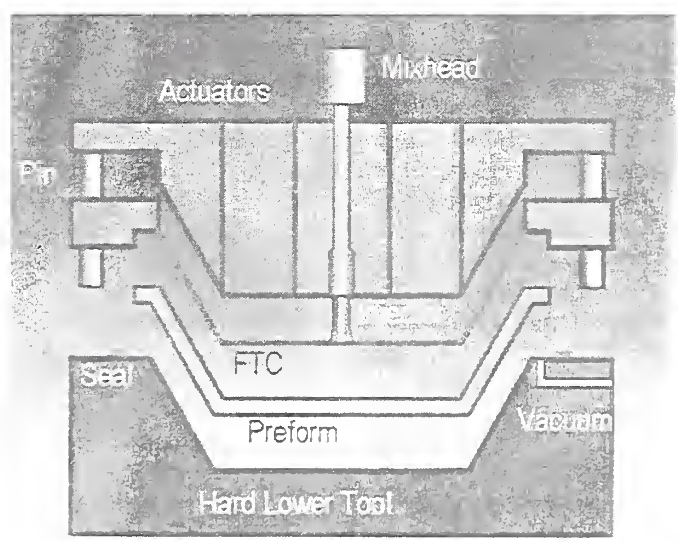


Figure 2. ZPM Tooling

The ZPM process begins with a preform. ZPM provides several advantages over a fixed cavity tool in the types of performs that can be used and their handling. A preform is placed into the lower tool and the FTC and its frame is locked in place. As vacuum is pulled in the cavity, the FTC is pulled into place and exerts a uniform pressure on the preform. The porosity of the dry preform insures even distribution of the vacuum without a separate media, as in aerospace practice. High loft preforms can be loaded into the tool and compressed to a high volume fraction, then compressed further under actuated pressure. This allows aerospace volume fractions to be achieved, and eliminates the problem of permeability variations seen in RTM tools where areas of high compression and gaps around corners are inevitable. Once the preform is loaded, clamping pressure is applied by the actuators to prevent the preform from being displaced during infusion. Pressure is then released on the injection zone and resin is rapidly injected into the tool (1-2 seconds), forming a reservoir between the FTC and the preform (Fig 3A). The zone is then

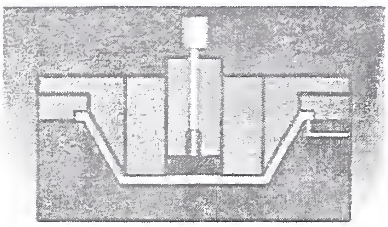


Figure 3A.

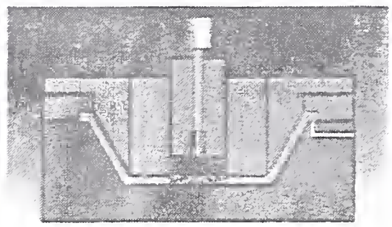


Figure 3B.

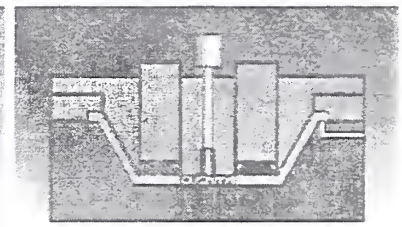


Figure 3C.

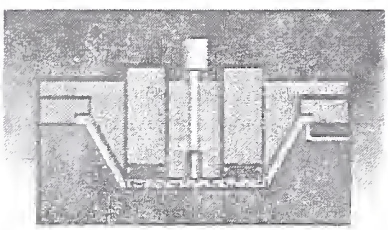


Figure 3D.

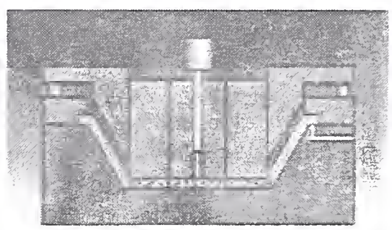


Figure 3E.

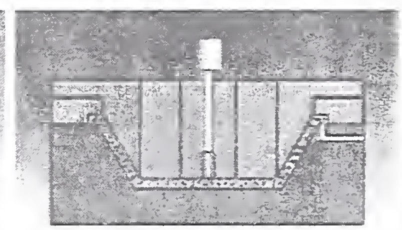


Figure 3F.

pressurized, forcing the resin through the preform (Fig 3B). Because the flow path is so short, the pressure drop is minimal, and the infusion proceeds as an extremely rapid, transient flow phenomenon. Pressure is then released in the adjacent zones, and the reservoir takes the path of least resistance, straining the FTC and flowing over the preform into the next zone (Fig 3C). The final clamping pressure on the previous zone is applied, determining the ultimate volume fraction. The next zones are pressurized (Fig 3D) and the reservoir transferred again (Fig 3E) until the part is infused. Total infusion time is dependant on resin and preform selection, but is independent of surface area, varying with the number of zones used instead. The speed of each step in the process is on the order of a second or two, allowing infusion of fast reacting resin systems before gelation.

3. Press Development. A ZPM test press was constructed to create test plaques, test actuation sequences, and verify flow simulations (Fig 4). The press has five computer-controlled zones that can be programmed to work with a wide variety of preforms and resins. After the preform is loaded, a small batch of resin is mixed and forced through the injector with a syringe. The injector is closed and the computer takes over and runs through its infusion sequence. The actuators can be switched between high, low, and exhaust settings, allowing different pressures to be used in the actuation and holding sequences. Sensor data is logged during the process, including video tracking of the flow front progression when a glass-bottomed mold is used. Initial testing focused on random-strand glass preforms, as they are the closest to meeting the cost requirements of volume automotive production. Preforms were tested for their compressibility characteristics in a custom fixture used with an Instron universal tester, allowing the volume fraction of the cured composite to be fine-tuned by varying the final holding pressure on the actuators. A series of experiments was run to determine whether the application of holding pressure on the dry preforms causes damage to

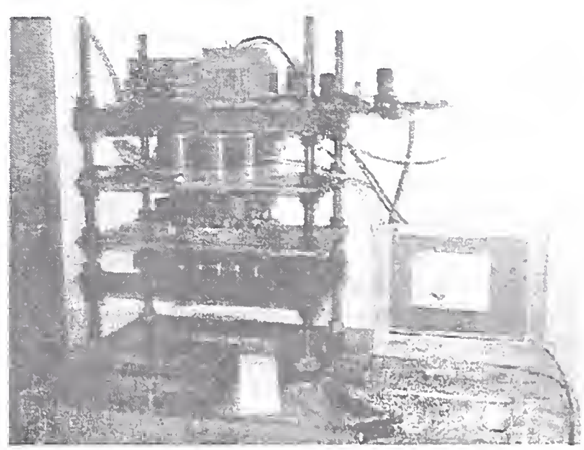


Figure 4. ZPM Test Press.

the glass fibers, but no loss of properties was detected with pressures up to 550 psi. The coupon test results show scatter matching the variability of the chopped strand mat weight. At a volume fraction of 55% (74% glass by weight), the test specimens showed a 43 ksi tensile yield strength and a 2.5 Msi modulus, very high numbers relative to chopped strand mat composites processed with conventional techniques. The raw materials cost for this composite is approximately $0.82/lb with a high volume performing process and polyester resin.

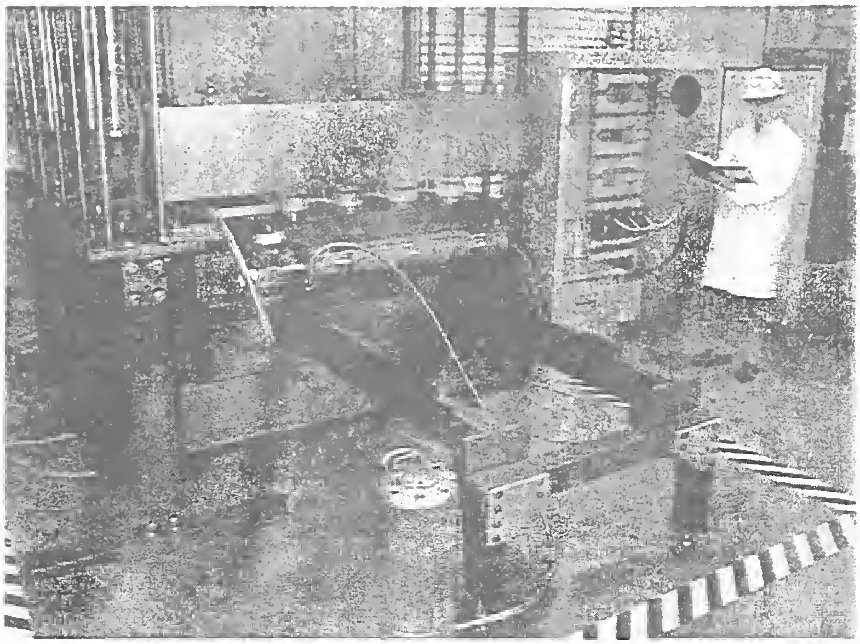


Figure 5. Full Size ZPM Press.

A larger press was designed to produce parts up to 55" x 65" in size, allowing experimentation with full-size tool design and optimization of total cycle time (Fig 5). Because of the low pressures used in the process and the incorporation of actuation into the tool rather than the press, a ZPM spec shuttle press can be very cost-effective, with robotic automation being the largest expense. The hydraulic actuators are powered by pneumatic cylinders, which act as accumulators, allowing several levels of pressure to be selected through a series of valves switched by an Interbus control system. Press platen deflection at maximum actuator pressure is less than 2.5 thousands of an inch across the entire platen, dropping to less than half a thousandth at a typical final holding pressure of 100 psi. Maximum loading is just under 1000 tons.

4. Simulation. SAR and its partner, Altair Engineering, worked to develop a functional 3D simulation package that could be used to test actuation sequences for complex parts with a minimum of trial-and-error experimentation. The benefits of flow simulation become more significant as tool complexity increases. The selection of the location of the zone boundaries across a part is an early part of the tool design that is difficult to alter after a tool is built, so being able to test an arrangement before cutting is critical. After that variable is fixed, the simulation is used to determine the sensitivity of the process on the inevitable variations in resin performance, so that changes in viscosity or reactivity can be compensated for in real time, with a high degree of confidence of how small changes will affect the filling of the tool.

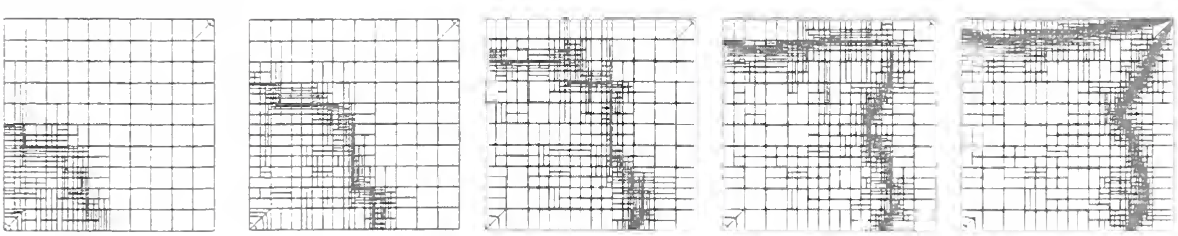


Figure 6. HP Adaptive Mesh.

To provide the necessary accuracy, the solver is fully three-dimensional, transient, and uses Altair's hp adaptive kernal to modify both the density and order of the mesh at each time step in the areas with the highest error. This last feature allows the use of a relatively coarse mesh, which is then refined at the flow front and de-refined after it, providing a drastic reduction in computational requirements (Fig 6). The software is designed to run on an SGI Origin 2000 parallel computing platform, but will also be functional on a multiprocessor Windows NT workstation by about 2002 as solver efficiency is optimized and workstation speed increases. The model used in the simulation

is a two-phase flow (resin and air or vacuum), weakly compressible, with full heat transfer including the mold and heating lines, with non-Newtonian flow and curing reaction kinetics. This requires the collection of a large amount of detailed property data for the simulation:

Preform	Resin
Volume Fraction: $v_f = f(P)$ Permeability: $K = f(v_f)$ Physical and Thermal Properties (Density, Compressibility, Specific Heat, Thermal Conductivity)	Viscosity: $\eta = f(\dot{\gamma}, T, \alpha)$ Reaction Kinetics $\alpha = f(t, T)$ $\Delta H_r = f(t, T)$ Physical and Thermal Properties

SAR uses a variety of techniques to gather the necessary data. Rotational rheometers are used to gather data on the reaction kinetics and low shear rate viscosity of the resins. Capillary rheometry is used to gather data on the higher shear rates and shear heating effects at shear rates of up to 1 million 1/s. Differential scanning calorimetry is used to characterize the thermal characteristics and reaction kinetics. All of this data has proven critical to accurate simulation, and is extremely useful in understanding the molding process. For example, the temperature dependence of the resin viscosity is usually very sensitive, with a 10 degree C change resulting in a factor of 5 change in viscosity for some of the resins used in ZPM. Because ZPM infusion is so rapid, shear rates can reach a level of 1 million 1/s or more. At this rate, shear thinning and heating combine to produce a viscosity drop of an order of magnitude. Characterization of the reaction kinetics also includes a series of experiments to determine the effects of increased catalyst and retardant concentrations on gel time and final degree of cure, so that shot-to-shot variations can be programmed into the injection equipment to compensate for variations in the process.

Figure 7. Rheology Lab.

5. Summary. SAR has developed the ZPM process to deliver aerospace composite performance while also meeting automotive cycle time and quality requirements. The through-thickness infusion of the resin under computer control allows the use of complex, engineered fabric preforms or chopped strand mat, and provides total cycle times in the 2-4 minute range required for high-volume production. The capital equipment costs for the process are substantially lower than sheet metal stamping or injection molding, as are the tooling costs. Proper characterization of the preforms and resins, combined with simulation tools from Altair engineering allow quality control programs to be developed with a minimal amount of trial and error.

6. Acknowledgments. This work was supported in part by a grant from the National Institute of Standards and Technology's Advanced Technology Program under the management of program director Jack Boudreaux. Additional assistance was provided by Altair Engineering and Rice University.

Combinatorial Materials Science: Application to Automotive Coatings?

Alamgir Karim
Eric J. Amis
NIST Polymers Division

Abstract. Combinatorial methods represent a new paradigm for materials research and for investigating fundamental and industrial problems in materials science. Combinatorial methods of drug discovery in pharmaceuticals research are well known and more recent applications of the methodology have led to the discovery and synthesis of new inorganic materials, catalysts, and organic polymers. We demonstrate that combinatorial methods are also well suited for studying material properties of polymeric coatings, known to play a critical role in automotive applications where their stability and integrity is of fundamental importance. The material properties of polymeric coatings are sensitive to a variety of factors such as composition, temperature, thickness, UV and moisture. Most polymeric coatings are also multicomponent filled blend materials and the miscibility and stability of the components is an important issue that affects their ultimate properties. To acquire data covering a range of variables is both time-consuming and expensive when done by traditional methods. Simple and elegant methods for combinatorial library preparation have recently been developed in the Polymers Division at NIST by leveraging expertise in polymer thin films and coatings. The novel approach developed included methods for depositing polymeric coating libraries that employ continuous gradients in thickness, composition, processing temperature, surface texture and patterning. Vast amounts of data can be generated in a few hours to help understand how these variables affect the material properties (e.g. coatings wettability or phase miscibility). A strong theory and modeling effort at the CTCMS (Center for Theoretical and Computational Materials Science) augments the combinatorial effort for increased understanding of materials behavior.

Structure, Surface Characterization and Modeling of Multiphase Polyolefin Blends and Composites

Charles C. Han
NIST Polymers Division

Abstract. Current emphasis of the multiphase materials program in the Polymers Division at NIST is focused on characterization and modeling of the interface, interphase and surface structures in polyolefin blends, and nano vs. regular composite structures formed during processing. Phase separated and partial crystallization in polyolefin blends and composites affect not only their mechanical performance, heat distortion and long term durability, but also the required coating conditions, surface properties, and appearance. We are currently using light scattering, depolarized low angle light scattering, synchrotron X-ray scattering, and optical and electron microscopy techniques to characterize the phase separation and crystallization kinetics and structure formation in polyolefin blends with and without nano-filler. Results on simultaneous and step-wise phase separation/ crystallization will be presented. Procedure for using these results in the development of a computer modeling tool will also be illustrated. The data are used for a finite element flow modeling program under development which could be used as a processing design tool in the future. This tool could have important use as a characterization and design aid in automotive parts design and properties prediction.

Advanced Force Controlled Robotics and Vision for Flexible Automotive Assemblies

Valerie Bolhouse
Ford
Matt Collins
Perceptron

Abstract. Manual assembly of automotive powertrain components is a repetitive process that presents the risk of injury to workers and the risk of mis-assembly. Automation of this process, in the form of a flexible assembly workcell designed for such applications as gear meshing of heavy transmission components, would eliminate these risks. To achieve this level of automation successfully, the Automated Powertrain Assembly Consortium, consisting of the Ford Motor Company (Dearborn, MI), Perceptron Inc. (Plymouth, MI), Progressive Tool and Industries Company (Southfield, MI), MicroDexterity Systems (Memphis, TN), and the National Center for Manufacturing Sciences (Ann Arbor, MI), are developing new approaches to manipulator design, three dimensional spatial location of objects, and manipulator control that allow the cell to *emulate human manual dexterity, touch, and vision.* The consortium is developing vision algorithms to determine identity and pose of components in semi-constrained dunnage from laser radar range images. They are also adapting a parallel-controlled, low-inertia robotic manipulator with high stiffness and accuracy of position for use in assembly applications. After developing the manipulator, its controller, and force-and vision-perception systems, the consortium will construct a prototype cell for evaluation. The enabling technologies are being developed and evaluated for integration this fall. This presentation will cover the development objectives and status to date. The consortium predicts that such technology could save the automotive industry more than $120 million a year and could be readily applied to the farm machinery, railroad transportation, and defense industries. The enabling technologies alone would increase U.S. market share in both the world machine vision and robot markets.

The Manufacturing Agility Server

Howell Mitchell
Flavors Technology

Abstract. This presentation will describe the objectives and current status of the Manufacturing Agility Server, NIST ATP project. This project developed new information technologies to improve the performance of robotic welding lines and other automated manufacturing processes. The program has demonstrated the ability to passively monitor production machines using their network connections, remotely determine the time history of their state, and to determine the performance impact of reassignment of particular operations to specific machines. This technology will provide great value to engineers who are commissioning new systems or making process improvements.

FIPER:
An Intelligent System for the Optimal Design of Highly Engineered Products

Michael W. Bailey, ***GE Aircraft Engines,*** **and William H. VerDuin,** ***OAI***

Turbine engine development is a highly coupled multi-disciplinary process. With ever increasing demands in life cycle costs, environmental aspects (noise, emissions and fuel consumption) and performance, the availability of accurate analytical tools during the design process is a given and ceases to be a discriminator between competitors. The application of these tools and their automated interaction in a robust computational environment may determine the success or failure of a project by reducing design cycle time and avoiding costly rework.

This paper describes pilot projects at GE Aircraft Engines (GEAE) that demonstrated benefits applicable to any highly engineered product. The support of a four year $21.5M NIST ATP (National Institute of Standards and Technology Advanced Technology Program) is enabling extension and generalization of these capabilities into the technologies comprising FIPER (Federated Intelligent Product EnviRonment), a web based environment that will support multi-disciplinary design and optimization.

The Opportunity

The development *of robust and optimal, highly engineered products and processes* to improve performance while reducing cost and cycle time seriously tax the capabilities of today's design systems. Further exacerbating the problem is the need to improve and control quality, for both internally manufactured parts and materials and parts produced through supply chains. Since products are now designed, manufactured and serviced at geographically disparate locations, the ability to share relevant product data is critical.

FIPER is an Integrated Multidisciplinary Design System which exploits the concept of the Intelligent Master Model, permitting context specific views of the Master Model, and seamlessly integrates relevant technologies to enable rapid instantiation and simulation-based evaluation of products and processes

The integrated multidisciplinary design environment under development will enable users to define process maps and rapidly integrate their own proprietary product-specific design and simulation tools through visual programming techniques. It will automatically provide access to a set of technologies including CAD systems and low and high fidelity analysis modules, as well as Multidisciplinary Optimization (MDO) and Robust Design technologies. It will also exploit Knowledge Based Engineering to capture rules and best practices.

Intelligent Master Model

The Intelligent Master Model is a major enhancement to the Master Model (MM) concept. Knowledge Based Engineering (KBE) is fused with Product Control Structure (PCS), conventional MM and Linked Model Environment (LME) to collectively render it an Intelligent Master Model. The IMM captures the intent behind the product design by representing the *why* and *how*, in addition to the *what* of a design. The geometric description is only one view of the information associated with the total product model. The IMM can also contain part dependencies, geometric and non-geometric attributes, manufacturing producibility and cost constraints. IMM can provide access to external databases, and can be integrated with proprietary and commercial codes through the LME. The IMM can capture and archive corporate design practices as well as design and manufacturing engineering expertise. This knowledge can enable less experienced engineers to consistently produce correct first time designs.

The IMM captures the process for generating the PCS at the conceptual and preliminary design level, which then flows the critical information to the detail design and manufacturing. The IMM uses its knowledge base to enable parametric scaling of designs in a top down fashion. When parameters must be computed by execution of simulation codes, the IMM manages this execution by working with process integration tools.

The Master Model

The Master Model captures requisite geometric and non-geometric information, to enable context-specific views of necessary design, manufacture, test, and service data. A product design system that supports early requirements definition and flow-down demands that the underlying representation be flexible to geometric, attribute, feature and knowledge-based changes. The traditional CAD representation is flexible only in a geometric sense.

The Master Model at the lowest or geometric level consists of parametric geometry features such as primitives, extrusions, holes, etc., which form the basic product description. Parameters associated with these geometric features are a subset of the key characteristics which are manipulated to define the product. At this level, the key characteristics include the traditional concepts of dimensionality (length, radius, angle, etc.), as well as those concepts that follow from knowledge-based solid modeling such as offset, spatial alignment, and perpendicularity constraints. Additionally, the existence of a feature is itself an attribute which may be turned on or off as needed to represent the part to varying fidelity levels. For example a bolthole is typically present during a stress analysis but omitted during a computational fluid dynamics analysis. This simplification would be part of the context model, thus creating a context-specific view of the geometry using feature suppression.

Using parametric feature-based technology, models are constructed by initially creating simple parametric block shapes to which features (e.g. flanges) are attached. Compound blends are then created and added to the model together with standard features such as radii and chamfers, to create the axisymetric solid. Finally, non-axisymetric features such as holes and slots are then added. This feature-based approach is consistent with feature based analytical model building and cost estimating, while also providing feature suppression functionality.

The initial approach to KBE was the encapsulation of product rules within UniGraphics XESS spreadsheets. These spreadsheets are linked to the geometry such that design rules and practices are parameterized to drive geometry. External codes such as those for disk design could also be executed. Thus an increase in flow thorough the compressor would initiate an aerodynamic resizing of blades and vanes resulting in a blade platform and attachment resizing combined with a disk redesign due to increased centrifugal loads. The whole compressor would thus "rubber band" or parametrically expand to accommodate increased flow.

The Product Control Structure

The PCS facilitates top-down control of the design, allowing the engineer to layout the system configuration and control changes in a top-down fashion. It facilitates *what-if* analysis at the conceptual, preliminary, and detailed design levels by allowing the designer to make parametric changes or to evaluate alternate configurations. This encourages design reuse and enforces standardization in the design process.

The PCS is a hierarchical decomposition of the product into its systems, subsystems and components (Figure 1). These are represented by high-level product attributes and key datum planes and axes to capture their spatial location and orientation. Once the top-level datums have been established and referenced by the subsystems, each subsystem can be designed independently in a distributed manner and later be automatically assembled. Within the PCS, components may be represented by preliminary, simplified geometry (e.g., 2-D cross-sections) or just datums. The cross-sections are picked from a library of cross-section types based on rules. The values for the parameters that define a cross-section are determined using rules captured in the knowledge base. The leaf nodes of the PCS become

Figure 1. Product Control Structure

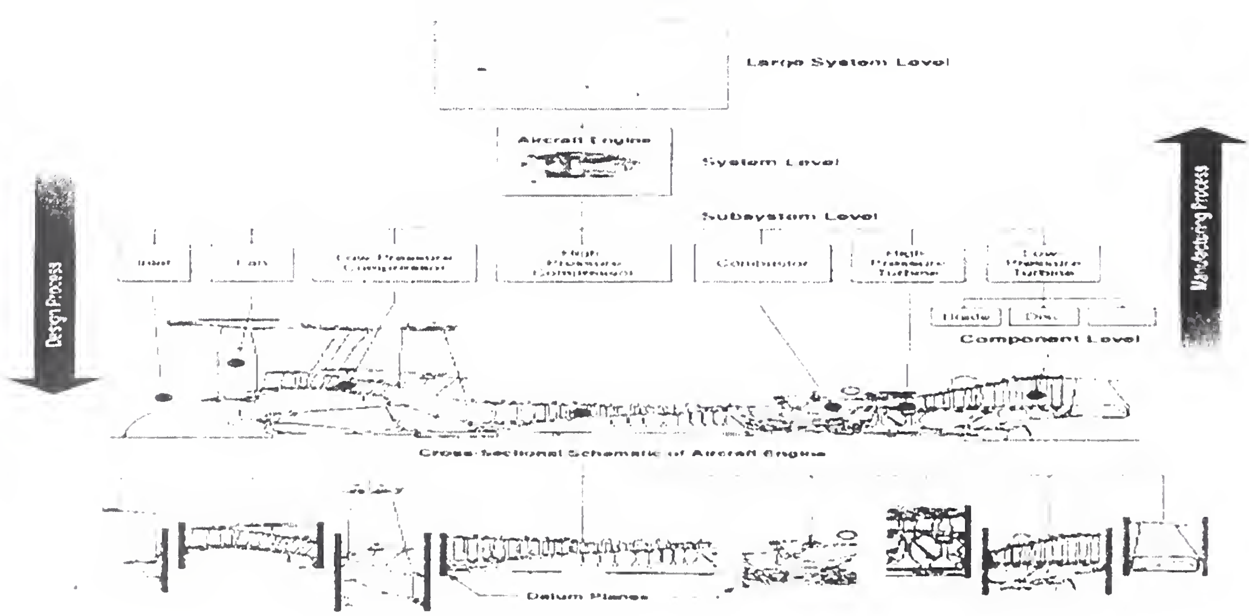
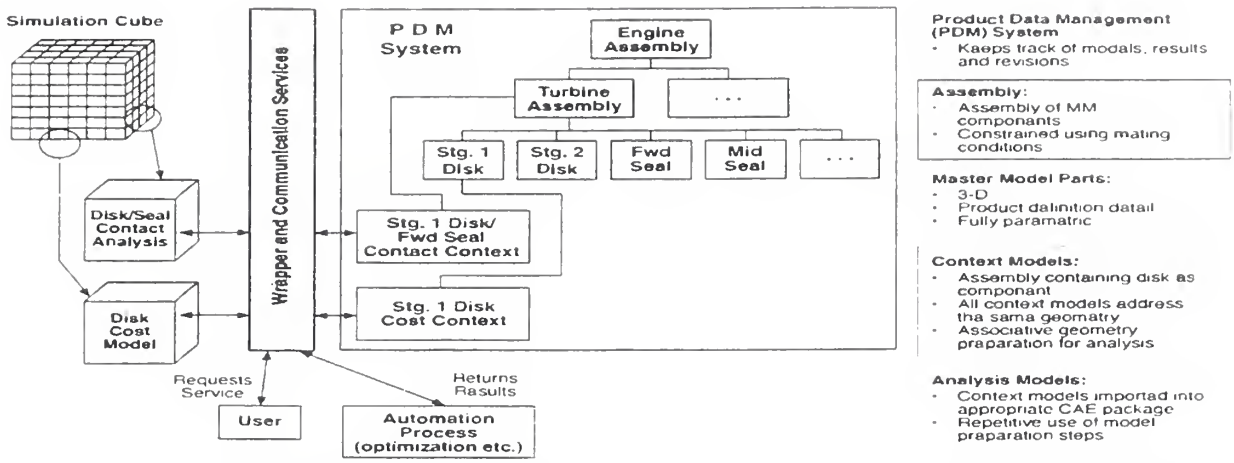


Figure 2. Linked Model Environment



the seed parts for the bottom-up design of the product into a 3-D assembly. The parts contain 3-D features to capture additional design and manufacturing intent. Everything is fully associative, and thus all changes to the PCS propagate throughout the model.

The Linked Model Environment

Disciplines such as stress analysis, heat transfer analysis, fluids or combustion analysis, and manufacturing and cost prediction each use their own abstraction of the physical model of the product. Within one discipline, several context-specific views may exist as the design evolves. For example, 2-D axisymmetric stress analysis models and detailed 3-D stress analysis models of various levels of refinement for the individual components of a jet engine are required. Each of these analysis models is associated with one or more simulation tools or codes, from simple response surfaces or performance maps during the conceptual design phase, to more complex analysis codes for detailed design, manufacturing process simulation, and cost modeling. This provides the promise of geometric zooming. Historically, these models exist in a heterogeneous environment, without explicit connections between them. Thus, a design change demanded by one disciplinary group has to be manually incorporated into all the various models of the product that co-exist; a process that is both tedious and error prone. Within the LME (Figure 2) a product's analysis and process models are linked to the M M so that all models are automatically synchronized to a single M M. Thus, a process is established by which design changes caused by one discipline are fed back to the M . A Product Data Management (PDM) system tracks the design revisions and the associated analysis views or context models of the product.

Design For Six Sigma

The goal of Design For Six Sigma (DFSS, 3.4 defects per million opportunities) is to create products and processes which are at Six Sigma levels of performance, manufacturability, reliability and cost. DFSS is based on an orderly process which identifies and flows down Critical to Quality (CTQ) characteristics for the product, process or service. This enables quality measures to be driven into the product during the early design phases where the cost of implementing changes is relatively low in comparison to fixing the problems later in the product life cycle. Key design factors for each CTQ are identified and statistical performance models are developed. Modeling, simulation, Design of Experiments (DoE) and analysis are usually employed to develop the statistical models. The essence of DFSS is to migrate from a deterministic to a probabilistic design approach. DFSS is generally focused on shifting means for CTQ's and reducing variances about means so that customer expectations are met at minimum cost.

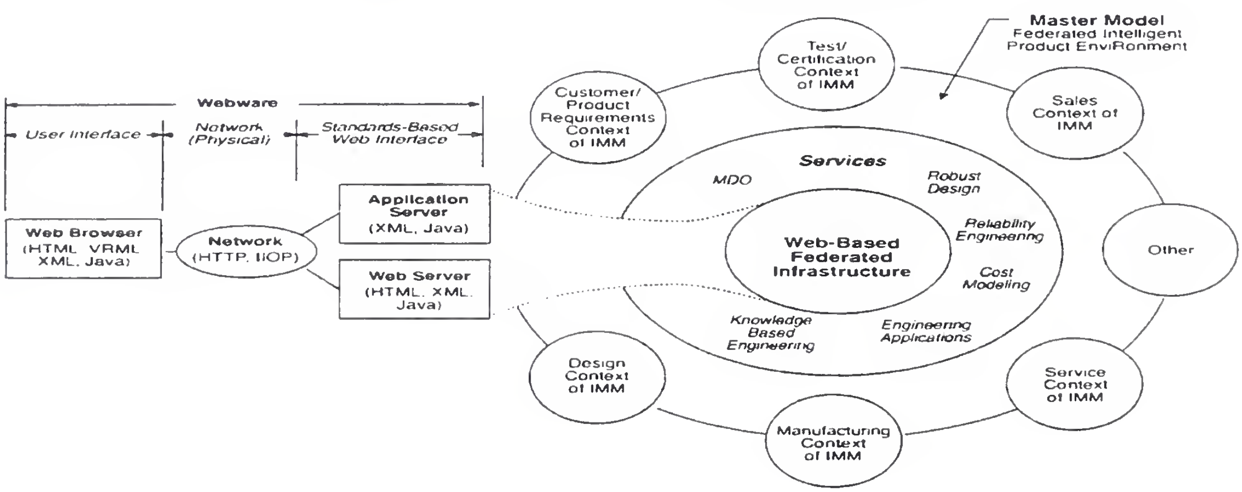
Robust Design is an intrinsic part of DFSS. Traditionally optimal design and robust design were viewed as independent technologies, but in fact there is great synergism and common core concepts that can be exploited to achieve optimal *and* robust designs for products and processes. Optimality and robustness often have competing objectives. The focus of the robust optimization problem is to simultaneously optimize the performance (mean of the response) and minimize the variation. In other words, a maximization problem would not merely strive for the highest peak, but would strive for a high plateau. *In practice this represents a trade-off between Performance and Technical Requirements, Reliability and Producibility*. This represents a paradigm shift in design methodology.

FIPER

FIPER represents a paradigm shift for product development through the introduction of a standards based product development environment Conceptually the FIPER environment is described in Figure 3 and in more detail in Reference1. Key elements include:

- Development of an extensible, standards-based plug and play, Web-based architecture to enable the creation of Six Sigma products and processes.
- Development and major enhancement of a set of advanced core technologies necessary to realize D F S S, most notably I M M, K B E, Robust Design, Multidisciplinary Design and Optimization, Cost Modeling and Producibility.
- Demonstration of FIPER on a diverse set of demanding applications, which span conceptual design, through manufacturing for systems, subsystems and components.
- Dissemination of the technology through a well founded commercialization plan, complimentary teaming, Web-based access, publications, educational programs and the creation of an early adoption program.

Figure 3. Federated Integrated Design EnviRonment



The FIPER team was chosen for their complimentary roles in achieving the overall FIPER objectives. GEAE is a complex engineering system developer and manufacturer and a Unigraphics CAD system user. Parker Hannifin is a complex aircraft engine and aircraft subsystem and component supplier and a ProEngineer CAD system user. BFGoodrichAerospace is a complex aircraft sub-system and component supplier and CATIA CAD system user. GE Corporate Research and Development (CR&D) has been developing the technology associated with IMM, KBE, MDO and DFSS for a number of years. Engineous Software Inc. is the commercializer for the FIPER software and their current product is iSIGHT, an engineering analysis process integration and optimization tool. Ohio University is providing computer system integration software wrapping tools and is developing a cost model that will be integrated with the IMM. Stanford University is creating producibility models that will be integrated with the IMM. OAI (Ohio Aerospace Institute) is the sponsoring organization and provides program administration. The complimentary teaming are key to the technical and commercial success of the FIPER project.

Reference 1: Röhl, P. J., Kolonay, R. M. et al. *A Federated Intelligent Product EnviRonment* AIAA-2000-4902, 8th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Long Beach, CA, September 6-8, 2000

Model Driven Intelligent Control of Manufacturing

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Extended Abstract

Common to all manufacturers of durable goods whether they are large or small or whether the product is simple or complex is the need to build things to print. Progress has been made in replacing the print with a digital product description. Comparable progress has not been made in the Numeric Controllers used to drive production machinery and fabricate parts. These controllers are still driven by G and M codes that date back to the 1950's. These codes do not adequately describe the end product, but merely specify a path of a cutting tool.

With the majority of CAD vendors introducing STEP (Standard for Product Data Exchange) data translators in recent years, manufacturers in Canada and the U.S. are discovering an effective way to exchange information and move into compliance with ISO 10303 [1]. From inception, the originators of STEP envisioned globalization and a content-rich data standard that would surpass the typical data standard supporting specific data entities and topologies. The design intent of STEP is to go far beyond its predecessor IGES to support not only 3D product data, but also product identification information, assembly structures, configuration controlled assemblies, manufacturing features and intelligence.

STEP-NC is an extension of STEP that defines data representing "working steps," that is, a library of specific operations that might be performed on a CNC machine tool [2]. In keeping with the STEP concept, these working steps are generic descriptions that can be incorporated into a product model. The descriptions are not linked to a specific format or code. However, STEP-NC working steps are roughly equivalent to the machining commands represented by traditional M and G codes with three dimensional geometry and feature definitions associated to the codes so that the machine tool can intelligently re-plan an operation when necessary.

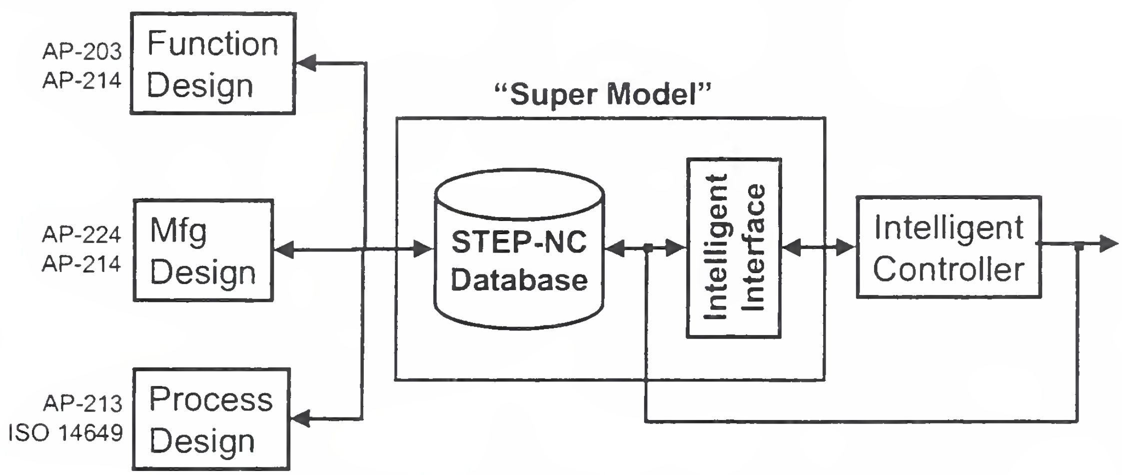

Figure 1. Model Driven Intelligent Control of Manufacturing.

"Model Driven Intelligent Control of Manufacturing" is a three year project to build a database, called the Super Model, to demonstrate the advantages of STEP-NC. Figure 1 shows it supporting a three stage design process- functional design, manufacturing design and process design- and delivering data produced by the process to an Intelligent Controller.

For the figure, functional design is assumed to produce a 3D product model description. The output can be described using AP-203 of STEP for the aerospace industry and AP-214 of STEP for the automotive industry with other Application Protocols (AP's) to be available for other industries.

Manufacturing design annotates the model with features suitable for the manufacturing processes on a shop floor. In STEP terminology, this model can be described using AP-224 for the aerospace industry and AP-214 for the automotive industry. Both AP's describe a range of features suitable for manufacture using milling and turning machines and other Application Protocols are to be available for other kinds of manufacturing processes.

Process design defines a manufacturing process for a specific type of machine. In STEP terminology, this model is to be described using a range of Application Protocols that have not yet been assigned numbers within the STEP framework. However, in the STEP-NC framework (developed by a "sister" committee of STEP in the International Standards Organization) the models are ISO 14649-11 for milling machine processing, ISO 14649-12 for turning machine processing and ISO 14649-13 for EDM machine processing. Also, AP-213 of STEP captures the "macro" process plan showing the production order between the machines.

The different kinds of design are performed by the same system or different systems. Three scenarios being considered by MDICM include:

— **Rapid Prototyping**. The functional and feature design is produced using an integrated CAD/CAM system at an Original Equipment Manufacturer (OEM). The result is output as an ISO 14649 model and read into an intelligent machine tool controller containing a shop floor path planning system. The tool controller is located at in-house shop of the OEM or belongs to a supplier. The path planning system in the controller dynamically defines a tool path for a tool selected by the operator and the part is cut.

— **Tooling**. Tooling for a production line such as a mold, die or fixture is designed by an OEM. The result is output as an AP-203 or AP-214 file and sent to a job shop. The job shop supervisor reads the file into a CAM system and uses that system to define manufacturing features that can be produced using the machines available in the shop. The result is output as a set of AP-224 files. Skilled operators read the AP-224 files into their own CAM systems and produce ISO 14649 files to make the selected features on their machine tools. Each 14649 file is read into a machine tool controller and used to cut a part.

— **Production**. The complete manufacture process for a production line is defined as an integrated AP-213/ISO14649 database containing the manufacturing sequence and the control files for each machine in the line. The database is used to configure the production run at set-up time and as an archive after the end of the production run. The database is developed using a combination of CAD, CAM and process planning tools.

The project has estimated business benefits for the first two scenarios. The basis of the benefits is the elimination of drawings as the primary means of communication between a customer and supplier. Today drawings are used because of the large range of systems used in industry. Consequently, engineers working for the OEM use a sophisticated CAD system to build a 3D product model and then make drawings (or their equivalents in IGES or a raster format) from that model. The drawings are sent by e-mail, FAX or regular mail to a supplier who then uses them to create a model of the product in a CAM system. The CAM system then reduces this model to the M and G codes allowed in the RS 274 standard and sends them to a machine tool controller.

If the 3D models made in the OEM CAD system are sent directly to the CAM and NC Controller systems of the supplier then everyone benefits because data does not have to be entered twice which wastes time, is error prone and produces a new model which is unlikely to be as good as the original. In the table the column labeled "With STEP" shows the time estimates for making a manufacturing process from 3D CAD data, and the column labeled "Without STEP" shows time estimates for making a manufacturing process from a drawing.

The benefits are compelling and have been verified by independent studies by Lockheed Martin and others. They can be supplemented by additional spreadsheets showing that the OEM will spend 75%less time

creating drawing information. Plus there are other less well quantified benefits that accrue from being able to reuse data more often, and from the controller being intelligent enough to prevent errors, optimize operations and dynamically re-create tool paths.

Process Planning Scenario							
	Without STEP				With STEP	Saving
	Max	Min	Average		Average	
Hours to make a process plan	100	4	16		12	25%
Hours to replan a process plan	20	1	4		3	25%
Number of iterations			3		2	33%
Total Hours			28		18	36%

Figure 2. Estimated Savings for Scenarios One and Two

However. to succeed the MDICM program must overcome significant technical and business barriers. There has been a long history of programs trying to make design and manufacturing process more efficient but failing because of the cost of new technology.

The technical barriers are caused by the complexity and size of the STEP and STEP-NC standards. STEP is developing the equivalent of a huge object model for industry. The model is much too large to be developed by the traditional approach of inventing one object for each real world item or concept. Instead a two step approach is taken where domain experts develop object models for their area of expertise and STEP experts break these objects down into fundamental components. The result is a "molecular" model in which each STEP standard defines how the objects required by an application domain are represented using a set of reusable, information atoms.

A STEP application only has to be able to implement the 500 atoms defined in the standard. This allows code to be reused across application domains and it allows enterprises to reuse their data across the product life cycle. However, STEP-NC is not just a data exchange process. An NC programmer needs to decide not only how to translate STEP-NC data into the internal model of a controller, but also how to interpret the commands in the manufacturing plan to make the part. Asking a programmer to both interpret the molecular composition of a STEP object from its atoms and decide how to execute the commands at the same time is challenging and may stop CAM and NC controller vendors from implementing the new standard

The goal of the "Intelligent Interface" shown in Figure 1 is to eliminate this barrier. This interface uses two new standards for data sharing: Part 14 called EXPRESS-X and Part 28 called STEP/XML. EXPRESS-X automates the process of constructing the object models from the information atoms stored in STEP. Therefore the programmer only has to understand the objects. XML is more descriptive than the Part 21 file format currently used by STEP and consequently easier to read and process. Together they reduce the technical barriers to STEP-NC by making it easier to understand and implement.

The business barrier for the MDICM program can be described by analogy to the problem that cell phones had in their early years. Today, cell phones are more convenient and more popular than regular phones. In their early days however, cell phones were inferior in coverage, weight and power, and cost more because the cell phone makes could not afford to loose too much money.

It is better for the supply chain to use 3D models than drawings, just like it is better to carry your phone in your pocket. However, in the early days STEP-NC software will be more expensive and "buggy" than traditional software. Consequently, the MDICM program needs to find its equivalent of the early cell phone user. These are likely to be OEMs using making prototype parts in in-house job shops (Scenario One). These users can afford to dedicate part of their shops to a new process and they will want to have expertise ready for the second stage when the larger and more sophisticated job shops start to use STEP-NC.

The MDICM project schedule requires us to demonstrate the partial manufacture of a part on a milling machine using three features at the end of the first year, to demonstrate complete implementation of the

STEP-NC process model for milling at the end of the second year, and to show the flexibility of the Super Model database by applying it to a new manufacturing process at the end of the third year.

In the first year there will be two pilot demonstrations. Both demonstrations will focus on an OEM making a part in an in-house job shop (Scenario One) . The first demonstration will be held at Benet Laboratories of Watervliet Arsenal in upstate New York. The Benet demonstration will use CADKEY for functional design, FB Mach for manufacturing design and EasyCAM for process design. The General Dynamics demonstration will replace EasyCAM with Virtual Gibbs for process design. CADKEY is a low cost CAD system that can read and heal the geometry of a wide range of other CAD systems. FB Mach is an advance feature based manufacturing system developed by Honeywell for the Department of Energy. EasyCAM and VirtualGibbs are CAM systems with light-weight options for dynamically generating tool paths on a controller.

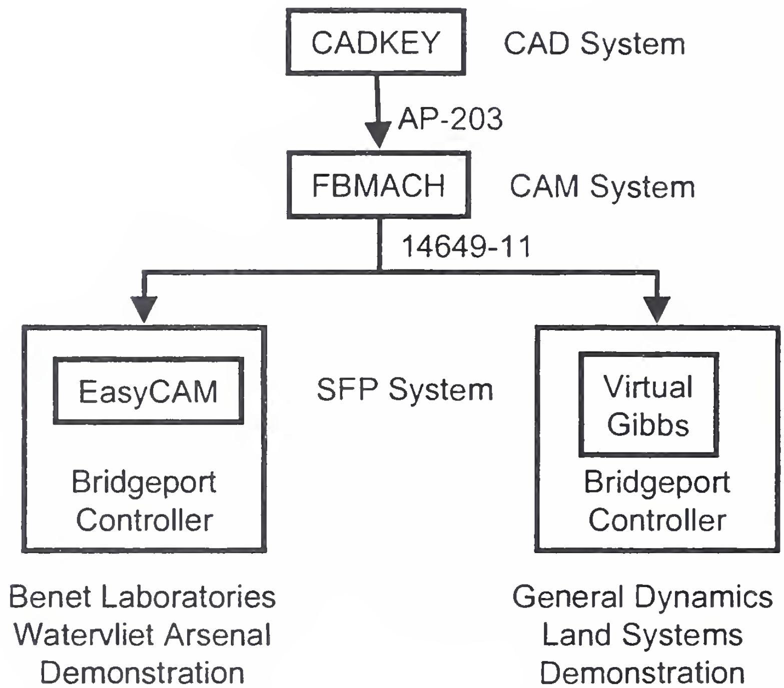

Figure 3. Configuration of the First Year Demonstrations.

Both demonstrations will use the on-board path planning system to develop the equivalent of the old style M and G codes. However, the external interface of the controller systems will now be ISO 14649 instead of RS274D. This is similar to an extension made to line printers several years ago where the old style standards used to drive dot matrix and line printers was replaced by Postscript. Internally, the printers still converted Postscript to the old style codes but everyone benefited from the reliability and efficiency of using a high level interface.

In the first year the business focus of the demonstrations is to show that the new standard can be used to replace drawings. In the second year, the benefits of the new process will be measured to show that the savings projected in Figure 2 are real. In the third year these benefits will be confirmed using STEP-NC for a new process.

References:

ISO 10303-1, 1994, *Industrial Automation Systems -- Product Data Representation and Exchange -- Part 1, Overview and Fundamental Principles*, International Standards Organization, Geneva, Switzerland.

ISO 14649-1, 2000, *Industrial Automation Systems – Data Model for Computerized Numeric Controllers -- Part 1, Overview and Fundamental Principles*, International Standards Organization, Geneva, Switzerland.